NASA/TM-2002-211769

AVST Morphing Project Research Summaries in Fiscal Year 2001

Anna-Maria R. McGowan
Langley Research Center, Hampton, Virginia

August 2002

The NASA STI Program Office ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Phone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

NASA/TM-2002-211769

AVST Morphing Project Research Summaries in Fiscal Year 2001

Anna-Maria R. McGowan
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

August 2002

Acknowledgments

The author gratefully acknowledges the invaluable, cross-disciplinary technical leadership of the Morphing Project team who are the primary reason for the success stories in Morphing in fiscal year 2001. Drs. Darrel Tenney and Richard Antcliff, and Messrs. Thomas Sutter and Long Yip have also provided crucial guidance throughout the year. The dependable support of Mss. Sherry Cox, Frances Sabo, and Pamela Stacy has also been essential to the Morphing project and are sincerely appreciated.

Available from:

NASA Center for AeroSpace Information (CASI)
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

Abstract

The Morphing project at the National Aeronautics and Space Agency's Langley Research Center is part of the Aerospace Vehicle Systems Program Office that conducts fundamental research on advanced technologies for future flight vehicles. The objectives of the Morphing project are to develop and assess advanced technologies and integrated component concepts to enable efficient, multi-point adaptability in air and space vehicles. In the context of the project, the word "morphing" is defined as "efficient, multi-point adaptability" and may include micro or macro, structural or fluidic approaches. The current document on the Morphing project is a compilation of research summaries and other information on the project from fiscal year 2001. The focus of this document is to provide a brief overview of the project content, technical results and lessons learned from fiscal year 2001.

Table of Contents

Introduction

The Aerospace Vehicle Systems Technology (AVST) Program office of the NASA Office of Aero-Space Technology has been developing coordinated research programs in which individual disciplines are supported in a collaborative environment to foster the development of breakthrough technologies. As part of AVST, the object of the Morphing project at the NASA Langley Research Center (LaRC) are to develop and assess advanced technologies and integrated component concepts to enable efficient, multi-point adaptability in air and space vehicles. This is accomplished by integrating smart, biologically-inspired, or other innovative approaches that lead to aggressive improvements in the adaptability, efficiency and safety of future flight vehicles. These improvements enable (1) improved vehicle resilience to safely address unforeseen problems; (2) extensive versatility to efficiently accommodate contrasting mission requirements; (3) and enhanced performance resulting in reduced operating costs. Additionally, technologies developed in the Morphing project may expose new capabilities and mission scenarios for future aircraft and spacecraft.

The Morphing project is an inherently multidisciplinary project, and has been built around a core discipline-based structure to provide the fundamental technology base. The key disciplines in the project include materials, structures, controls, flow physics, multidisciplinary optimization, biology, and electronics. The discipline-based research activities are integrated to support the project application areas that include micro-aero adaptive control, adaptive structural morphing, and biologically-inspired flight systems (see figure 1). Smart and biologically-inspired technologies and advanced component concepts are currently under development for each application area. In some cases, the technologies are consolidated into devices that have local sensing and feedback control. For many applications, these devices will modify local phenomena to support a macroscopic strategy, such as flow separation control for advanced high lift systems. Consequently, a combined approach to control systems and system identification is being used in the Morphing project to address the control laws and controller responses required for the individual devices, as well as addressing global requirements for distributed arrays of devices to achieve an overall system benefit. At the system level, multidisciplinary design optimization will take advantage of the tools developed in the program to optimize the component technologies and provide a systems approach to component integration.

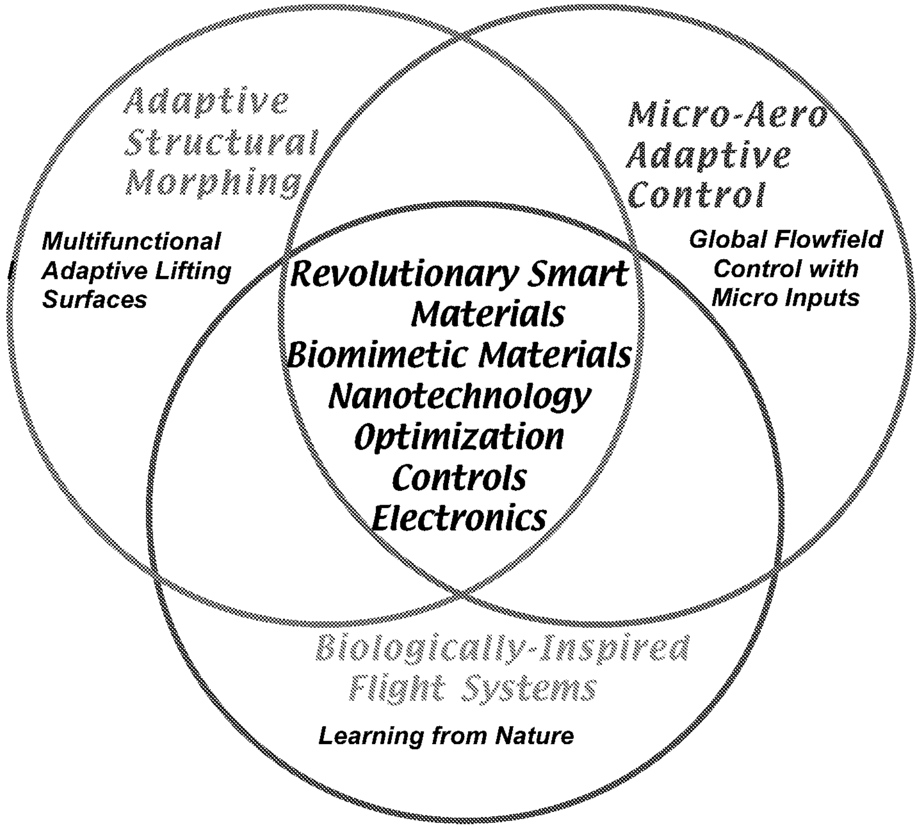


Figure 1. Major components of the fiscal year 2001 Morphing Project

This document provides a compilation of summaries of the research conducted in the Morphing project in Fiscal Year (FY) 2001. Each summary was written by the lead researcher of a specific research effort (called a work package). The lead researcher should be contacted directly for more detailed information on any work package. Other documentation that provides broad overviews of the past and present project is references [i]. The current document begins with a summary of the organization of the research in FY 2001, followed by the research summaries. The Appendix contains a listing of formal publications, invited lecturers, external organizations and the Morphing project team in FY 2001. The focus of the current document is the technical results and lessons learned of the project in FY 2001. A project plan with milestones is available upon request.

The Morphing Project in Fiscal Year 2001

In fiscal year 2001, all research activities in the Morphing project were organized into five areas: Micro-Aero-Adaptive Control, Smart Technologies, Adaptive Structural Morphing, Biologically Inspired Flight Systems and BIOSANT (which is jointly managed with the SLMFST Project in AVST). Each project area included several work packages as shown in Table 1. In FY 2001, the Morphing project included approximately 70 person years of effort and had a gross budget of \$10.6M. Due to the multidisciplinary nature of the project, over 34 different branches at NASA Langley Research Center and one branch from NASA Dryden Flight Research Center were involved in the project in FY 2001. In addition, in FY 2001, the project incorporated numerous collaborative research efforts with external organizations. A complete listing of the external organizations is provided in the Appendix. A lecture series on morphing related topics was initiated in FY 2001 to broaden our knowledge and foster further interactions with external researchers. A listing of the lectures is also provided in the Appendix.

---

[i] 3, 27, 28, 55, 59

Work Packages and Lead Researchers in Fiscal Year 2001 in the Morphing Project

Micro-Aero Adaptive Control - Anthony E. Washburn

Maneuvering Control	
Periodic Excitation for Forebody Vortex Control	D. Bruce Owens
Virtual Shape Change Research	Fang-Jeng Chen
Fluidic Thrust Vectoring	Larry Leavitt
Noise Attenuation	
Active Control and Prediction of Jet Noise	Kevin W. Kinzie
Closed-Loop Control of Cavity Shear-Layer Instabilities	Michael A. Kegerise
Performance Enhancement	
Simplified High Lift System	LaTunia Pack
Smart Surfaces for Drag Reduction	Michael Walsh
Active Transonic Drag Reduction Through Shock Spreading	Maria Bobskill William E. Millholen
Fundamental Tool Development	
Advanced Sensors for Flow Control	Kenneth Wright
Actuator Development for MAAC	Norman W. Schaeffler

Smart Technologies - Robert G. Bryant

Electroactive Polymers and Modeling of Electroactive Materials	Joycelyn Harrison
Flex Circuits and Cables	Kevin N. Barnes
Microwave-driven Smart Membrane Actuators	Sang H. Choi
Performance Characterization and Design Optimization of Macro-Fiber Composite Actuators	W. Keats Wilkie
MDO Techniques and Novel Aircraft Control Systems	Sharon L. Padula
Flight Control Technologies for Adaptive Aerospace Vehicles	David Raney

Adaptive Structural Morphing - Lucas G. Horta

Smart/Bio-Inspired Concepts	
Biomimetics Ways to Create Efficient Multifunctional Structures	Dawn Jegley
Adaptive Wing Structural Concepts	Thomas Jordan
High-Rate, Morphable, Hingeless Control Surface Demonstrated in the TDT	Jennifer P. Florance
SAMPSON-Smart Aircraft and Marine Projects System Demonstration	Jeffrey D. Flamm

Wind Tunnel Performance Evaluation	
Langley Adaptive Aeroelastic Demonstrator	Robert Scott
Structures Technology Development	
Elastic Tailoring and Active Control of Wing Structures	David M. McGowan
Multifunctional Adaptive Structures	Travis L. Turner
Synergistic Tailored Design of Metals and Structures	Kimberly S. Bey
Autonomous Adaptive Control Systems	Randolph Cabell
Modeling/Validation	
Feedback Control Using Piezoelectric Actuators: Do's and Don'ts	Lucas G. Horta Mercedes C. Reaves
Probabilistic Approach to Model Update of the Aerostructures Test Wing (ATW)	Lucas G. Horta Mercedes C. Reaves David F. Voracek
Aerostructures Test Wing (ATW) Excitation system Design and Performance Test	Mercedes C. Reaves Lucas G. Horta David F. Voracek
Development of a Self-Sensing Piezoelectric Actuator	Lucas G. Horta Mercedes C. Reaves Garnett C. Horner

Biologically-Inspired Flight Systems - David E. Cox

Biomimetic Long Endurance Vehicle Systems	
Biologically-Inspired Flight Concepts	Barry Lazos
Autonomous/Collaborative Control of Aeroelastic Fixed Wing Micro Aerial Vehicles: Characteristics of Fixed Wing Micro-UAVs	Marin R. Waszak
Component Technologies	Robert Fox Qamar Shams
Swarming and Airmass Guidance	
Airmass Guidance	David E. Cox
Aerodynamics and Control of Flapping Flight	
Dynamics and Control of Resonant Flapping Micro-Aerial Vehicles	David Raney

BIOSANT - Emilie J. Siochi

BIOSANT (Joint effort with the SLMFST project)	
Biologically-Inspired Fabrication of Electroactive MAV Wings	Emilie J. Siochi

Table 1. Work Packages and Lead Researchers in Fiscal Year 2001 in the Morphing Project

Micro-Aero Adaptive Control FY 2001 Research Summaries

Periodic Excitation for Forebody Vortex Control

D. Bruce Owens, 757-864-8450, d.b.owens@larc.nasa.gov
Vehicle Dynamics Branch, Airborne Systems Competency

Background Information:
At a significant angle-of-attack, a forebody will shed vortices. If the forebody is some distance from the center-of-gravity, mechanical and continuous blowing pneumatic devices have shown that these vortices can be manipulated to produce favorable yawing moments.

Objective of Current Work:
To evaluate the use of advanced fluidic effectors which use the technique of periodic excitation for the purpose of forebody fluidic control in a simple, lightweight, and seamless manner for aerospace vehicles. The yaw control produced by manipulating the forebody vortex flow field will be shown to provide control power for enhanced maneuvering and stability augmentation.

Benefits over Existing Systems:
This research uses active flow control to manipulate the forebody vortices. The benefit over previous methods would possibly be easier system integration and lower power requirements.

Previous Work on This Work Package:
During FY 2000, an existing generic fighter model was modified to accept a synthetic jet actuator into the chined forebody. The characterization of the actuator mounted on the two different types of nozzles (normal and tangential blowing) was accomplished using a hot wire anemometer, and the velocity fields around the actuator/nozzle configurations were documented at a wind-off condition, and the actuator frequency effects were also measured and documented. Wind tunnel testing was conducted in the 12-Foot Low-Speed Tunnel. These tests showed, using a flow visualization technique, that blowing using the synthetic jet was able to create an asymmetric vortex flow field around the forebody of the model. Surface pressure measurements confirmed the flow asymmetry. However, no measurable yawing moment coefficient was produced.

Current Year Accomplishments:
During FY 2001 a smooth round forebody for a different but comparable generic fighter has been designed and built that incorporates a new actuator that should produce higher velocities and flow rates. The forebody is designed with numerous parameters, e.g., blowing location both circumferentially and longitudinally, blowing direction, nozzle size and shape, forebody apex shape - rounded to pointed, fineness ratio, multiple simultaneous blowing locations. Instrumentation for the model will include: standard six-component strain gauge balance, steady and unsteady pressure measurements on the forebody. This model will be tested during the October-November 2001 timeframe in the 12-Foot Low-Speed Wind Tunnel and the March 2002 timeframe.

Lessons Learned:
As there was no wind tunnel testing performed during FY 2001 this section is not applicable.

Future Work:
If the present research is successful then future research will include placing these morphing devices in a free-flying generic fighter model. The free-flight technique will allow for the evaluation of the stability and control authority offered by the devices in a six-degree of freedom environment. This future research will also include control law design and possible additional static and dynamic wind tunnel tests to refine the characterization of the devices.

Virtual Shape Change Research

Dr. Fang-Jenq (Frank) Chen, 747-864-5732, f.j.chen@larc.nasa.gov
Flow Physics and Controls Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

Background Information:
Conventional airfoils of aerospace vehicles have been designed for a single flight condition and then modified to cover multiple flight conditions. This is done through the use of control surfaces, such as ailerons and flaps. The control surfaces affect changes in the flow field by directly varying the camber on certain regions of the airfoil, thereby causing changes in the structural and aerodynamic characteristics of the entire airfoil.

Objective of Current Work:
The primary objective of virtual shape change research is to develop a cost-effective flow control system that has the potential for revolutionary advances in aerodynamic performance and maneuvering compared to conventional approaches.

Benefits over Existing Systems:
The development of such systems has many implications for aerospace vehicles including: reduced mechanical complexity, lower energy consumption, enhanced maneuvering, and agility with enhanced aerodynamic performance and safety.

Previous Work on this Work Package:
Previous work on this work package was to develop powerful synthetic jets for practical flow control applications. To date, the velocities generated from the LaRC synthetic jet actuator are among the largest in the world. Details of the characteristics and performance of the LaRC synthetic jet actuator had been investigated and documented.

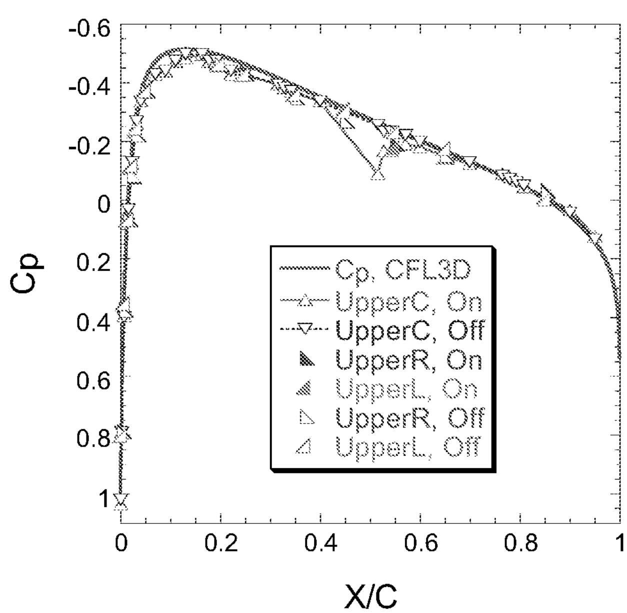
Current Year Accomplishments:
A two-dimensional NACA 0015 airfoil model was designed to test mild maneuvering capability of synthetic jets in the NASA Langley Two feet by Three feet Tunnel. The goal is to assess the applicability of using unsteady suction and blowing to alter the aerodynamic shape of an airfoil to enhance lift and/or to reduce drag. The effect of virtual shape change on the airfoil model was detected by comparing the measurements of airfoil surface pressures with the synthetic jet actuation on and off. Typical variations of the surface pressure coefficient, C_p, with actuation at $x/c = 0.5$ on the upper surface are shown in figure 1. It clearly indicates a localized increase of the surface pressure in the neighborhood of actuation. That causes a –7 percent change of the airfoil upper surface lift as shown in figure 2. The lift change drops to zero at higher freestream velocities. With synthetic jet actuation near the leading edge ($x/c = -0.015$), it appears that the stagnation line is shifted inducing an effect similar to that caused by small positive angle of attack to produce an overall positive lift increase. Details of the test results with synthetic jet actuation at different chordwise locations, different forcing frequencies and amplitudes, and different freestream velocities are currently under analysis.

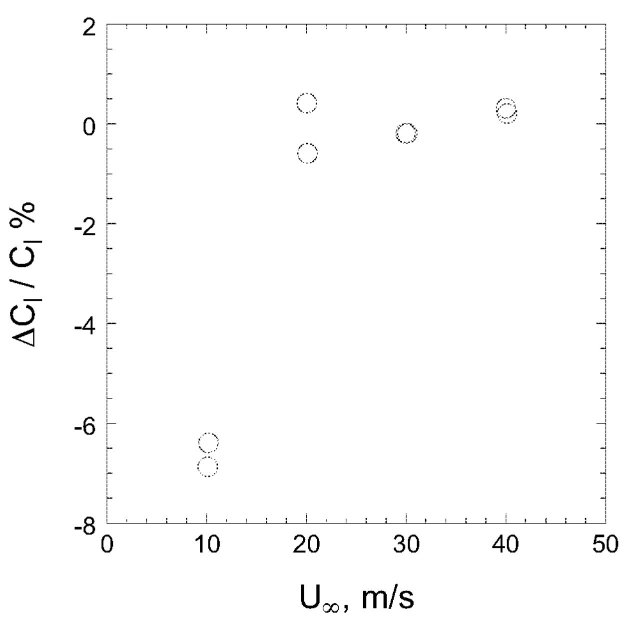
Lessons Learned:
Need more powerful synthetic jet actuators for virtual shaping in practical applications.

Future Work:
Improve synthetic jet actuator design or develop new actuators to provide enough flow control authorities for aerodynamic virtual shaping.

Formal and Informal Documentation Available:
1. Chen, F. J. *Virtual Shaping of a Two-dimensional NACA 0015 Airfoil Using Synthetic Jet Actuator*. Submitted to the 1st AIAA Flow Control Conference, June 24-27, 2002, St. Louis, Missouri.
2. Chen, F. J. *Development of Synthetic Jet Actuators for Active Flow Control at NASA Langley*. Presented at the AIAA Fluid 2000 Conference, AIAA Paper 2000-2405, June 19-22, 2000, Denver, Colorado.

External Partners and Their Accomplishments:
A research grant to Professor Douglas R. Smith and an undergraduate research assistant, Amanda Bridges, University of Wyoming. Their work was published in the AIAA Paper 2001-2774: *The Influence of Orifice Orientation on the Interaction of a Synthetic Jet with a Turbulent Boundary Layer*. The 31st AIAA Fluid Dynamics Conference & Exhibit, June 11-14, 2001, Anaheim, California.





Fluidic Thrust Vectoring for Control

Larry Leavitt, 757-864-3017, l.d.leavitt@larc.nasa.gov
Configuration Aerodynamics Branch, Aerodynamics, Aerothermodynamics & Acoustics Competency

Background Information:
Although mechanical thrust vectoring offers substantial control authority, external moving surfaces are not signature compatible and can be extremely heavy and complex.

Objective of Current Work:
Develop and demonstrate fluidic injection (FI) and fluidic thrust vectoring (FTV) technology for application to a variety of exhaust nozzle geometries, airframe configurations, and operating conditions. FTV is, and will continue to be, an enabling technology for seamless flight control because of the inherent advantages and control power provided across the speed range.

Benefits over Existing Systems:
Especially important is the contribution of thrust vectoring at low speeds (i.e., low dynamic pressure) where other seamless control technologies are either ineffective or extremely limited. Fluidic thrust vectoring offers improved signature and reduced weight compared to thrust vectoring with mechanical moving hardware.

Previous Work on This Work Package:
1. Completed design and fabrication of multi-axis thrust vectoring nozzle for testing in JETF.
2. Completed Jet Exit Test Facility (JETF) testing of multi-slot fluidic injection nozzle.
3. SOW to initiate time-accurate version of PAB3D for use in unsteady calculations to Dryden. Waiting for funding to be re-guidelined to DFRC.

Current Year Accomplishments:
1. Completed static testing in JETF of multi-axis thrust vectoring nozzle.
2. Initiated methodology in TetrUSS code, USM3D in particular, for calculating the internal performance of nozzle simulations. Gained understanding for setting initial conditions required to "start" the nozzle flow. Influenced work to continue on k-e turbulence model methodology in USM3D.
3. Time-accurate PAB3D methodology completed and tested for steady state cases. Preliminary data, validating the unsteady flow over a cylinder (figure 3) at various diameter, M, Re, dt and grid density, agree very well with experiment.

Lessons Learned:
1. Bellows design for propulsion testing is extremely difficult. Well-made metal bellows (a lost art?) are required for this particular propulsion simulation system.
2. Pressure distributions from USM3D simulation with SA turbulence model compared well with PAB3D results for conditions with no separated flow in nozzle, (figure 1). As expected, SA turbulence model and wall function do not appear to be adequate for nozzle simulations with separated flow, (figure 2).

Future Work:

1. Complete initial CFD computations to identify best conceptual design. Initiate detailed design and fabrication of Gen 1 throat shifting FTV models. (2/2002)
2. Complete JETF tests of Gen 1 throat shifting FTV concepts. Initiate final report of experimental and computational results. (9/2002)
3. Complete USM3D methodology for calculating the internal performance of nozzle simulations. Complete simulations using k-e turbulence model and compare to PAB3D data, experimental data, and USM3D simulations completed in FY 2001 with SA turbulence model.
4. Initiate a time-accurate PAB3D simulation of fluidic thrust vectoring with pulsed injection.

Formal and Informal Documentation Available:

Proposed AIAA paper for the 32nd AIAA Fluid Dynamics Conference, titled *Propulsion Simulations with the Unstructured-Grid CFD Tool, TetrUSS.*

External Partners and Their Accomplishments:

Analytical Services & Materials (AS&M) has completed the time-accurate PAB3D methodology and is currently validating unsteady test cases. Preliminary data of unsteady flow over a cylinder agree well with experiment, (figure 3).

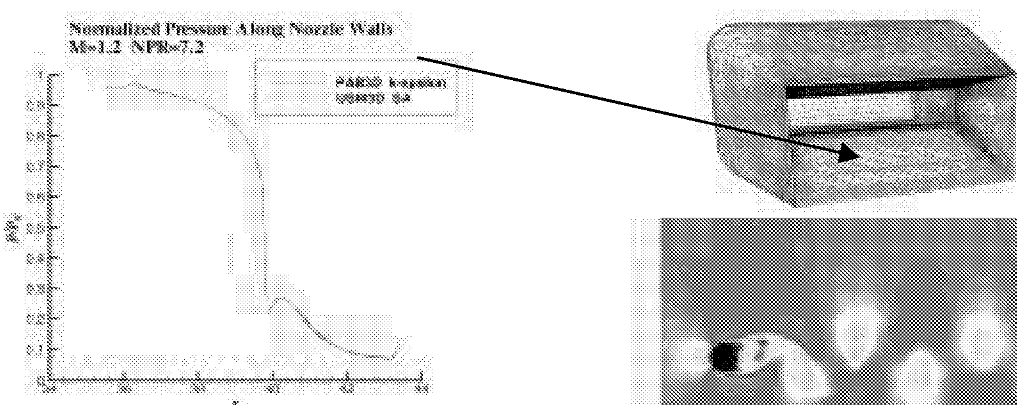


Figure 1. Fluidic Jet Effects Model.

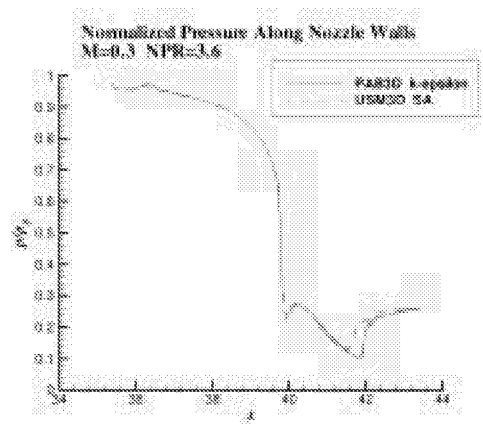


Figure 2. Fluidic Jet Effects Model.

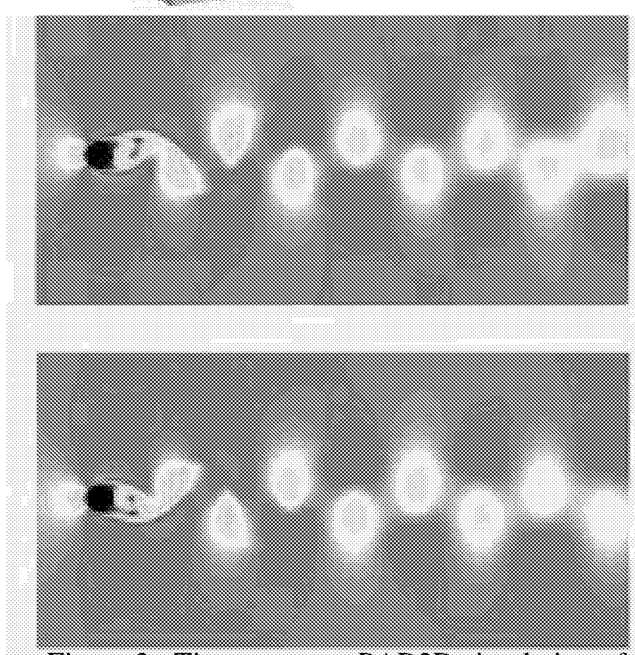


Figure 3. Time-accurate PAB3D simulation of vortices shedding off of a cylinder.

Active Control and Prediction of Jet Noise

Kevin W. Kinzie, 757-864-5375, k.w.kinzie@larc.nasa.gov
Aeroacoustics Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

Background Information:
Jet noise is a limiting technology on many aircraft systems if federal and community standards of aircraft noise are to be met. Passive mixing devices can reduce the radiated noise, but the most effective noise suppressors typically have unacceptable associated thrust losses. Active control techniques are desired that can be optimized to meet mission requirements with minimal thrust loss. In addition, jets that morph into various shapes could exploit the beneficial aeroacoustic properties of nonround jets.

However, jet noise is a broadband source distributed over a relatively large spatial distance making standard approaches to active flow and noise control problematic. Peak noise sources are typically located downstream external to the jet, further complicating active control schemes. High Reynolds number jets are not very sensitive to actuator inputs making it difficult to gain necessary control authority to alter jet development. Jet engine applications also have extremely high exhaust temperatures that would damage or destroy many conventional flow control actuators.

Objective:
The ultimate objective of this work package is to develop validated technologies for understanding, predicting, and controlling jet exhaust noise emissions for a wide class of aerospace vehicles that include conventional subsonic transports, futuristic unconventional transports, military vehicles, and aerospace transportation systems.

Benefit over Existing Systems:
If successful, active control techniques could be used to reduce the radiated noise from commercial and military aircraft with minimal performance losses since the system could be actuated as needed and optimized for mission performance. Spinoff technologies could lead to devices that improve the mixing characteristics of jets and reduce infrared signatures or hot jet impingement problems.

Current Year Accomplishments:
<u>Small Scale Experiments</u>
Mean and fluctuating flowfield measurements were made in a Mach 0.3, 0.6, and 0.85 jet. Since a comprehensive understanding of the jet flowfield is at the heart of any noise reduction strategy, these experiments lay the groundwork for future work. Extensive tests were performed to evaluate the performance of several different dynamic pressure sensors to determine which model would best measure the fluctuation levels of boundary layer instabilities at the jet exit. High sensitivity and frequency response are required for this measurement. Figure 2 shows the results comparing 2 each of 2 different sensor types and figure 3 shows the coherence function between sensors 1a and 1b indicating high levels of azimuthal coherence below 20 kHz. The sensor measurements agree reasonably well up to approximately 22 kHz, but then begin to diverge. The cause of the difference between sensor types is not known. Similar tests will be performed later this year with a full array of transducers to characterize the nozzle boundary layer exit conditions. In addition, these experiments will be used to aid in the development of time accurate jet simulation methods that would ultimately lead to noise prediction capability.

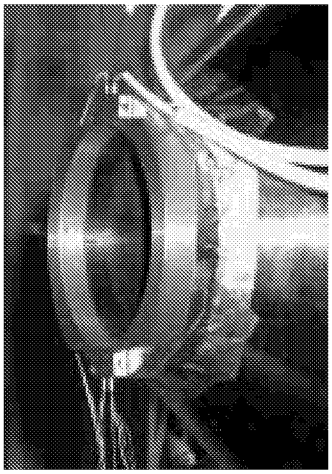


Figure 1. Miniature pressure sensors installed at nozzle exit.

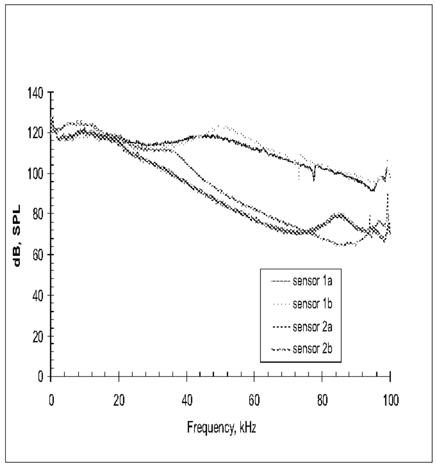


Figure 2. Comparison of pressure fluctuation levels at nozzle exit between sensor brand 1 and 2.

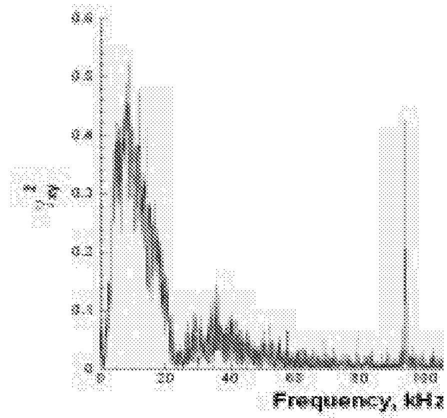


Figure 3. Coherence between two sensors with azimuthal separation at nozzle exit.

Fluidic Jet Shaping

Fluidic jet shaping is a concept by which either the mean jet plume shape or the unsteady fluid dynamic modes are controlled or altered using air injection or some other type of actuation technique. The idea is to achieve the same fluid dynamic and noise characteristics as fixed mechanical hardware designs using an appropriate actuation system. As our understanding of jet fluid dynamic processes and noise generation mechanisms develop, fluidic injection or active control systems could be used to force the jet to develop in a desired manner.

Preliminary CFD analysis of a separate flow nozzle system at typical takeoff cycle conditions was performed with air injection introduced at the trailing edge. Sample results are shown in figure 4 and demonstrate that air injection can be used to induce streamwise vorticity similar to mechanical chevron mixing noise reduction devices. Proof-of-concept testing is planned in the Low Speed Aeroacoustic Wind Tunnel later this year.

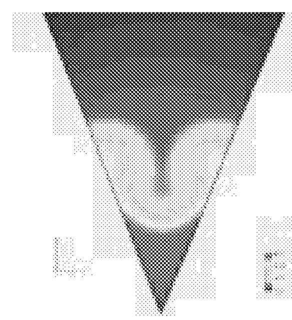


Figure 4. Cross section of total temperature in a circular exhaust jet showing mixing induced by fluidic injection.

External Partners:

A grant with Notre Dame University is in place to explore low order modal decomposition of the jet using the proper orthogonal decomposition (POD) technique. Once the technique is successfully applied to the jet flow, attempts will be made to control the flow using an array of plasma actuators structured to alter the most energetic POD modes. Notre Dame made progress this year constructing the jet facility, fabricating the POD hot-wire rakes and performing initial testing.

Lessons Learned:

Important lessons were learned this year in both the computational and experimental areas. The time accurate simulations demonstrated the need for a much finer grid resolution to capture the small scales needed to describe the jet noise related turbulence. Finer grid resolution while solving a smaller portion of the jet plume is planned for this year. In the experimental area, the difference between the high frequency response of the different transducer manufacturers when used in the jet flow was unexpected, especially since the controlled calibrations showed comparable performance out to 100 kHz. This will lead to additional complexity when making jet measurements in the high frequency regime.

Closed-Loop Control of Cavity Shear-Layer Instabilities

Michael A. Kegerise, 757-864-7815, m.a.kegerise@larc.nasa.gov
Flow Physics and Control Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

Background Information:
The flow over a cavity is characterized by a complex feedback process that leads to large-amplitude, self-sustained oscillations of the pressure, density, and velocity fields in and around the cavity. In aircraft weapons bays, where the rectangular cavity is the canonical geometry, the high-level sound pressure levels (~170 dB) associated with the flow oscillations can be damaging to weapons and sensitive instruments stored within the bay. Current solutions to the problem are centered on passive devices that often are only applicable for a small range of flight conditions.

Objective of Current Work:
The objective of the present work is to use active flow control technologies for cavity resonance suppression through the manipulation of shear-layer instabilities. The ultimate goal is to achieve suppression of cavity resonance from low subsonic to supersonic Mach numbers through the use of an adaptive control system.

Benefits over Existing Systems:
Current solutions to the cavity problem are centered on passive devices. Typically, these devices are chosen to minimize the flow oscillations for a given flight Mach number and cavity geometry. At off-design conditions, the flow oscillations are often exacerbated by the presence of the control devices. An additional drawback of existing passive control systems is their inability to suppress the multiple frequency modes often present in cavity flow oscillations.
A closed-loop adaptive control system can address these deficiencies in existing systems.

Previous Work on this Work Package: This work package was new for FY 2001.

Current Year Accomplishments:
Three areas were focused on for FY 2001:
1. Baseline characterization of the cavity model.
2. Actuator design and characterization.
3. Preliminary closed-loop control tests to verify the suitability of the actuator for cavity control.

The baseline characterization involved unsteady pressure measurements in a cavity with a length-to-depth (L/D) of 5.0 over a range of freestream Mach numbers. In this way, the cavity resonant modes were identified and were found to be in agreement with previous measurements reported in the literature.

In cavity control, the primary problem is one of disturbance rejection. In particular, it is desired to minimize or eliminate the upstream traveling disturbances that reach the cavity leading edge. To this end, an actuator for cavity flow control must be able to introduce disturbances of the proper character (both in frequency content and amplitude). The precise performance requirements for cavity actuators are, however, only partially known. For the present model, a bandwidth of up to 2 kHz is desired. The required actuator output levels are largely unknown at the present time. To meet the bandwidth requirements, a piezo-driven synthetic-jet actuator was chosen. The slot exit of the synthetic jet was located at the cavity leading edge and oriented such that it introduced disturbances parallel to the freestream direction. Hot-wire measurements of the velocity at the slot output revealed the peak velocity to be greater than 15 m/sec over a bandwidth from 600 to 1500 Hz.

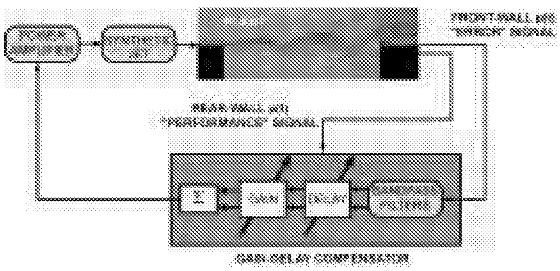


Figure 1. Schematic of digital gain-delay feedback controller

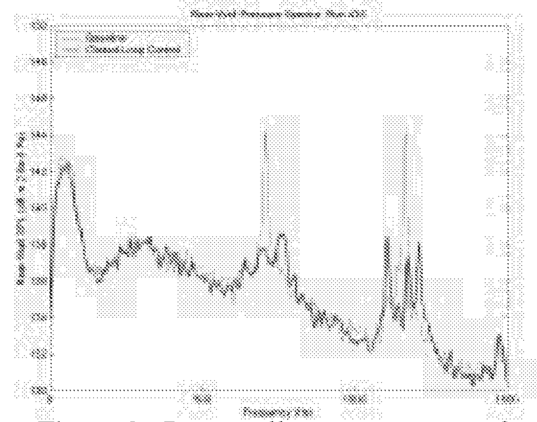


Figure 2. Rear-wall pressure spectra for baseline and control cases with M=0.35 L/D=5.0

As a precursor to the adaptive control tests to be performed in FY 2002, a simple digital gain-delay controller was tested. The primary objective was to verify that the synthetic-jet actuator, when used as part of a feedback controller, was capable of suppressing cavity oscillations. The results of these tests will also serve as a baseline for comparison to the results of upcoming adaptive control tests. A schematic of the gain-delay feedback controller is shown in figure 1. The gain-delay compensator shown in the figure was implemented on a dSPACE real-time processor. To set the compensator parameters, the rear-wall pressure was monitored in real-time as the gain and delay were adjusted for each mode frequency. The "performance" signal was minimized when the gain and delay were set to their optimal values. A sample control result for optimally tuned compensator parameters is shown in figure 2. The baseline, uncontrolled spectrum is shown for comparison. The controller is able to reduce the resonant mode amplitudes at 700 and 1170 Hz by 7.0 and 6.5 dB respectively. The results provide confidence that the synthetic-jet actuator can control multiple cavity modes in a closed-loop control system.

Lessons Learned:
It is necessary to control ALL cavity modes simultaneously. Experiments with the digital controller revealed that when a single mode is suppressed, another mode could be destabilized and increase in amplitude. Required actuator authority is still an unknown quantity and experiments are planned for FY 2002 to answer this question. This information is paramount to extend active control to higher Mach numbers (> 0.4).

Future Work:
A number of adaptive control algorithms will be tested in FY 2002 to identify those best suited for cavity control. New actuator designs (cantilever beam actuators) will be tested and experiments will be performed to answer the question of required actuator authority.

External Partners and Their Accomplishments:
A grant is in place with the University of Florida for the development of system identification and adaptive feedback control algorithms that will be applied to the cavity flow problem.

Simplified High Lift System

LaTunia Pack, 747-864-1618, l.g.pack@larc.nasa.gov
Flow Physics and Control Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

Background Information:
Conventional high lift systems employ a moveable slat and a moveable flap often comprised of several parts to generate the lift required for take-off, landing and loiter. These complex systems are expensive, heavy and maintenance intensive. A systems study performed by The Boeing Company indicated that significant cost and operational savings could be obtained if the current typical high lift system could be replaced by a simply hinged slat and flap system with periodic excitation used to control separation. The current effort followed a comprehensive feasibility study at flight Reynolds numbers.

Objective of Current Work:
The objective of the current work is to simplify high lift systems by replacing the slotted slats and flaps with a simply hinged slat and flap and use periodic excitation to the control flow separation at the slat and flap shoulders.

Benefits over Existing Systems:
Cost, weight and operational savings.

Previous Work on This Work Package:
Early separation control research funded by this program included separation control on a 10" chord NACA 0015 tested at the 0.3-m Transonic Cryogenic Wind Tunnel. This research was aimed at investigating the effect of Reynolds number on the use of zero-mass-flux oscillatory blowing for separation control. Two configurations of the NACA 0015 were tested. The first configuration was a straight NACA 0015 with control applied near the leading edge to delay stall. The second configuration tested was the same airfoil but with a 30 percent trailing edge flap deflected 20 degrees and control applied at the flap shoulder. Oscillatory blowing was shown to be effective at controlling leading edge separation on the first configuration and separation off the flap of the second configuration. More importantly, these results were obtained at flight Re numbers. Further testing included separation control on generic 2D and 3D configurations to enable unsteady CFD validation. These promising results and the industry systems studies, lead us to apply the active separation control technique to a high lift system.

Current Year Accomplishments:
A modified version of the EET (Energy Efficient Transport) supercritical airfoil was tested in the Basic Aerodynamic Research Tunnel (BART). The supercritical airfoil has a simply hinged 15 percent chord leading edge slat that can be deflected from 0 to 30 degrees and a 25 percent chord simply hinged flap that can be deflected from 0 to 60 degrees. The test focused on controlling flow separation at the slat shoulder of the model. The main reason for this was the lack of an actuator with the appropriate control authority for the flap region, where the space limitations are severe. These limitations would be significantly alleviated on real systems that are at least 10 times larger than the current model. An actuator comprised of piezoelectic disks was used to produce periodic excitation for controlling separation at the slat shoulder. The primary reason for deflecting the slat is to eliminate the possibility of laminar LE separation or LE stall; thereby

increasing the lift generated. For slat deflections higher than 10 degrees, the flow separates from the slat shoulder and the slat actuator is effective at controlling that separation. With control from the slat actuator stall is delayed by 1 to 2 degrees and the maximum obtainable lift is increased as shown in figure 1.

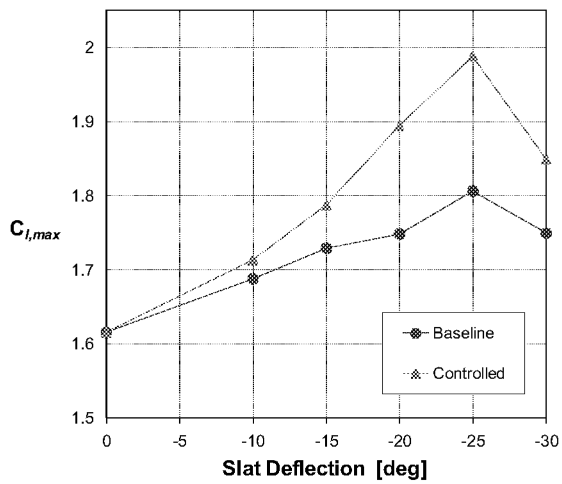


Figure 1. The effect of slat deflection on the baseline and controlled maximum lift coefficient. Flap deflection =4.3°, Reynolds number=750,000, both LE actuator slots used, f=853Hz, $C\mu$=0.03%.

Lessons Learned:
The key lesson learned was that stereolithography is not a suitable method for building actuators to be employed directly for the simplified high lift model. However, stereolithography worked very well for rapid actuator prototyping and for testing actuator performance prior to final design and manufacturing using conventional machining. The current test was the first demonstration of active separation control off the slat shoulder of a simplified high lift system.

Future Work:
During FY 2002, the simplified high lift model will be tested with both a slat and flap actuators. The slat actuator kept the flow attached up to x/c~0.70 and increased lift. With the flap deflected and flap actuator active it is anticipated that the flow will remain attached to the flap, allowing increased flap deflections and enhanced lift.

Formal and Informal Documentation Available:

1. Lin J. C. and Dominik, C. J. *Parametric Investigation of a High-Lift Airfoil at High Reynold Numbers*. Journal of Aircraft, Vol. 33, No. 4, 1997, pp. 485-491.
2. Seifert, A. and Pack, L.G. *Oscillatory Control of Separation at High Reynolds Numbers.* AIAA Journal, Vol. 37, No. 9, 1999 pp. 1062-1071.
3. Seifert, A. and Pack, L.G. *Active Control of Separated Flows on Generic Configurations at High Reynolds Numbers*. AIAA Paper 99-3403, June 1999. Submitted to AIAA Journal 2001.
4. McClean, J. D., Crouch, J. D., Stoner, R. C., Sakurai, S., Seidel, G. E., Feifel, W. M., and Rush, H. M. *Study of the Application of Separation Control by Unsteady Excitation to Civil Transport Aircraft*. NASA CR-1999-209338, 1999.

5. Pack, L.G., Schaeffler, N.W., Yao, C.S., and Seifert, A. *Active Control of Flow Separation from the Slat Shoulder of a Supercritical Airfoil*. Extended Abstract Submitted to the 1st AIAA Flow Control Meeting, St. Louis, June 2002.

External Partners and Their Accomplishments:
The work is done in collaboration with Dr. Avi Seifert, currently a Professor at Tel Aviv University. Dr. Seifert worked on flow control, in particular separation control, for more than a decade before bringing his expertise to Langley Research Center in 1996, as an NRC research associate. Since 1996 he has worked with Langley personnel in demonstrating that oscillatory blowing is effective for active separation control at Reynolds numbers comparable to an aircraft at take-off, on swept airfoils, at compressible speeds, on thicker airfoils and also applied the method to vector and rotate turbulent jets.

Smart Surfaces for Drag Reduction

Mike Walsh, 757-864-5542, m.j.walsh@larc.nasa.gov
Flow Physics and Control Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

Background Information:
The turbulent boundary layer skin friction represents approximately 50 percent of the total drag of a commercial transport and 90 percent of the total drag for underwater vehicles. A successful 25 percent turbulent boundary layer skin friction reduction technique translates into a $1.25 Billion estimated annual savings for the airline industry. In the 1980's a viscous drag reduction program conducted at LaRC resulted in the development of Riblets that give a 6 percent turbulent skin friction reduction. The drag reduction performance of the Riblets was demonstrated from low speed tests to flight conditions. To date, the Riblets is the only turbulent skin friction technique validated at flight conditions. Currently the Riblets have seen only limited application on commercial aircraft. In the late 1980's, NASA had demonstrated that the riblets would give the drag reduction, Boeing and 3M were looking at the application on commercial aircraft. The application of the Riblet film to a large transport initially took 3 weeks. At that time, Boeing was not willing to proceed because of the long application time. The 3M Company had been developing the Riblet film for about 10 years and the person in charge retired. At that time, 3M put it on the back shelve until Boeing could make a stronger commitment. In the mid 1990's, Airbus was more proactive with the film and ended up eventually putting the film on several scheduled transport aircraft.

Objective of Current Work:
During the 1990's active turbulent skin friction reduction techniques have been examined in numerous CFD studies but very few experimental studies. Also there has been a great deal of research and development on MEMS technology. The objective of the present program is to examine active as well as passive turbulent skin friction techniques that can eventually provide a practical method that will give large skin friction reductions for aircraft.

Benefits over Existing Systems:
The Riblet concept is the only successful skin friction reduction technique that has been demonstrated at flight conditions. The performance of Riblets is approximately 6 percent.
A successful program will result in 10-25 percent skin friction reductions.

Current Year Accomplishments:
The literature has been extensively reviewed. Based on this review, two concepts have been selected for initial evaluation: traveling waves and near wall vortex generators. CFD studies have shown that the spanwise traveling wave may result in reductions as large as 30 percent. The dramatic effect on the near wall region is shown in figure 1 from Du and Karniadakis (2000). The yellow-red indicates high-speed regions and the blue indicates low speed regions of fluid. The top figure is characteristic of the normal near wall structure. When the traveling wave is imposed on the flow, the data shows dramatic changes in the near wall structure. Fabrication techniques have been identified and initiated to provide a surface with suitable wavelengths and frequencies.

There have been several limited experimental studies showing that near wall vortex generators (VG) can be used to modify the near wall structure. Fabrication techniques are being identified to provide VG's on the small scales of the near wall structure.

Lessons Learned:
There are numerous CFD studies on active turbulent skin friction reduction techniques but few experimental studies. A large percentage of the previous studies indicate that the near wall region modification has the potential for large skin friction reductions. The limitations for experiments and applications are the small dimensional scales of the near wall region of the turbulent boundary layer. Langley Research Center has the low speed facilities and instrumentation capability required for this research.

Future Work:
Obtain experimental verification of the above two techniques.

Formal and Informal Documentation Available:
No formal publications at this time. A review paper is in progress to summarize the findings of the literature review.

External Partners and Their Accomplishments:
A grant was awarded to the University of Texas at Austin to examine the traveling wave concept in March 2001.

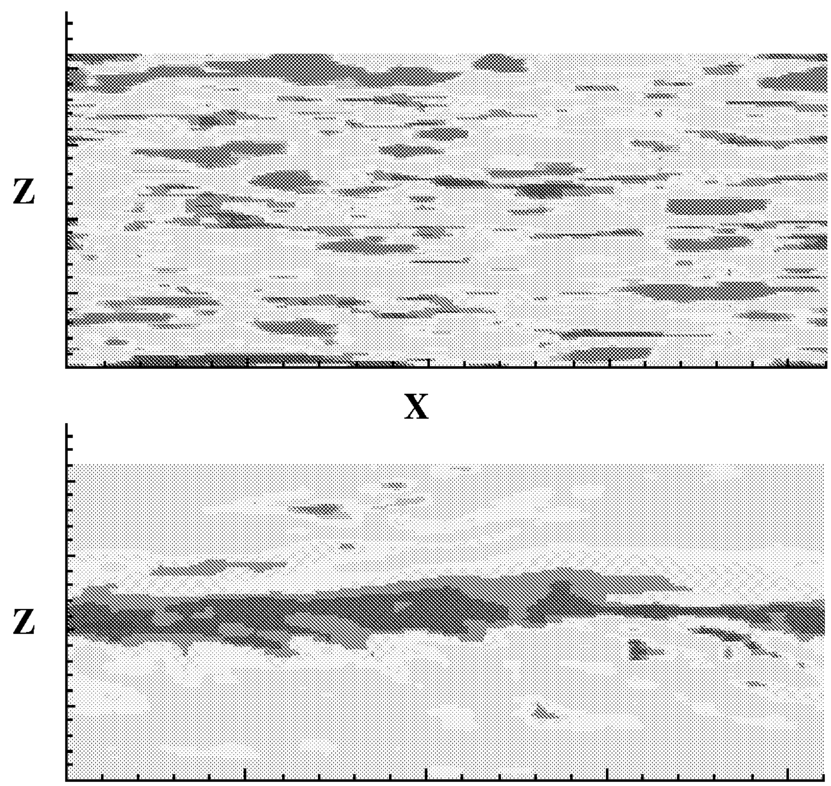


Figure 1. Visualization of near wall with (bottom figure) and without spanwise traveling wave control (top figure).

Active Transonic Drag Reduction Through Shock Spreading

Maria Bobskill, 757-864-5064, m.v.bobskill@larc.nasa.gov
William E. Milholen II, 4-7867, w.e.milholen@larc.nasa.gov
Configuration Aerodynamics Branch, Aerodynamics, Aerothermodynamics , and Acoustics Competency

Background Information:
The area of transonic drag reduction has been a long-standing topic of research, which has been fueled largely by the commercial transport industry. Aerodynamic prediction codes and testing techniques have been developed which allow designers to develop aircraft that perform efficiently at design conditions. Methods to improve the off-design performance of commercial transports are always being examined, as the off-design characteristics often play a strong role in the sizing and/or range of a given configuration.

One method, which has been proposed to improve the off-design performance of a transonic aircraft, is a wing that can change shape, or "morph" to mitigate adverse off-design effects. A frequent goal of improving off-design performance focuses on reducing drag, particularly the wave drag generated by shock waves on the aircraft. Thus, a wing that could locally change shape to decrease the shock wave strength would be highly advantageous.

The current research examines the size and shaping of a small "bump" on a cruise wing upper surface, as a means by which to spread the shock wave, and thereby reduce transonic drag for off-design conditions. On an aircraft, the bumps would be part of an active system, whereby they would be deployed in an intelligent fashion to minimize drag. Thus, an aircraft designed to take advantage of such an active drag reduction system would have an increased range and reduced operating costs.

Objective of Current Work:
Develop reductions in transonic drag by spreading and decreasing shock wave strength on an airfoil or wing. The size and shaping of small bumps on a cruise wing upper surface will be examined as a means by which to spread the shock wave, and thereby reduce drag for off-design conditions. Computational fluid dynamics analysis codes coupled with various design methods will be used to design and examine the effect of static bumps on the shock wave strength for a two-dimensional airfoil at off-design conditions. Promising geometries will be experimentally evaluated.

Benefits over Existing Systems:
The Europeans have conducted similar research, but do not appear to have utilized advanced computational based design methods.

Previous Work on This Work Package:
The FY 2001 point of contact was Maria V. Bobskill (4-5064), who is responsible for the computational accomplishments discussed below, and portions of the literature review.

Current Year Accomplishments:
A literature review was performed to assess the state of the art in this area and gather valuable information on previous lessons learned. A candidate airfoil was chosen (NASA EET). The baseline airfoil was analyzed using the unstructured flow solver FUN2D, with the required grids

generated using AFLR2. Planning for the experimental phase was begun, focusing on the 0.3 meter Transonic Cryogenic Tunnel at LaRC. The possibility of using smart materials to activate the bumps during future wind tunnel tests has been considered, and discussions were held with Travis Turner of the Structural Acoustics Branch and Paul Roberts of the Model Systems Branch.

Lessons Learned:
The literature review indicated that passive shock wave control using porous plates over cavities in the vicinity of the shock wave often leads to an increase in drag, due to the tendency of thickening the boundary layer. The addition of suction downstream of the cavity can help, but the results tend to be mixed. Suction applied upstream of the shock wave is not an efficient means to reduce wave drag, as the suction thins the boundary layer, often moving the shock wave aft, and increasing its strength.

The literature review also indicated that a local contour change on the airfoil upper surface near the shock wave, in the form of a bump, can be effective in reducing the shock wave strength and thus the wave drag contribution. In general the viscous drag is not significantly affected since separation is often delayed. As expected the bump height and location play a major role in the optimization for off-design conditions. The addition of suction upstream of the bump may further help reduce wave drag. However, the addition of a suction system to the experimental model will cause a significant increase in the experimental model cost and complexity, which will require careful consideration before deciding to add this capability. Unless some type of unsteady suction system is used, the mass flow requirements and supporting systems will probably prohibit any consideration by aircraft manufacturers.

Obtaining 2-D airfoil test data will be challenging at the transonic test conditions planned for this investigation. First, the model size will need to be small to help alleviate some of the model/wall interference concerns that may confound the results of this study. Currently, the plan includes fabricating and testing a NASA EET airfoil model with a 6-inch chord that has a removable upper surface section for testing different contour bump designs. Testing in the 0.3-m TCT with this size model will require the use of the adaptive walls (floor and ceiling) to further minimize the wall interference effects. The analytical software used to adjust the adaptive wall system to curvatures for minimal wall interference is no longer available because of tunnel computer and control system upgrades. Therefore, various analytical results will be needed before the test to estimate tunnel floor/ceiling contours at desired test conditions to achieve minimal wall interference. Another challenge includes implementing a schlieren system for off-body visualization of the shock to provide location and shock character information. A schlieren system has been implemented in this facility in the past, but is not currently considered a turnkey system for routine use and will require some effort to locate and reassemble its components. Even with these challenges, the use of the 0.3-m TCT is desirable because it is a continuous flow facility (allowing longer on-point times) that will enable testing at flight Reynolds numbers.

Future Work:
During FY 2002, the computational design and analysis of bumps on the upper surface of the NASA EET airfoil will continue. Several design methods will be examined. In addition, planning for the experimental evaluation of the bumps will continue, with model design and fabrication for a test in the 0.3-meter Transonic Cryogenic Tunnel. The use of shape memory alloys, or other deployable materials, will continue to be examined, with possible experimental evaluation during a follow up experiment.

Unsteady Circulation Control for Enhanced Vehicle Performance

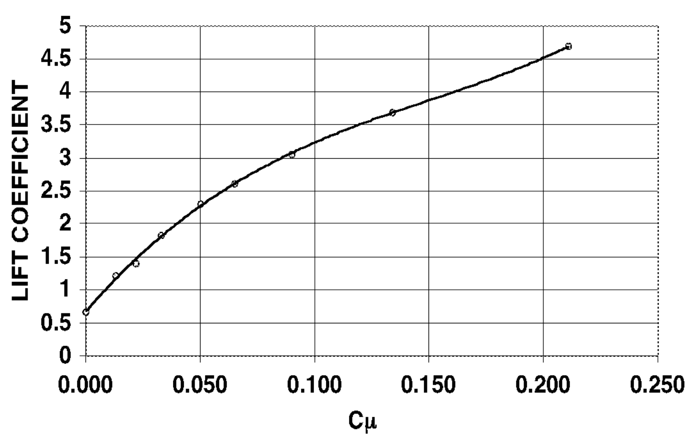
Gregory S. Jones, 757-864-1065, g.s.jones@larc.nasa.gov
Flow Physics and Control Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

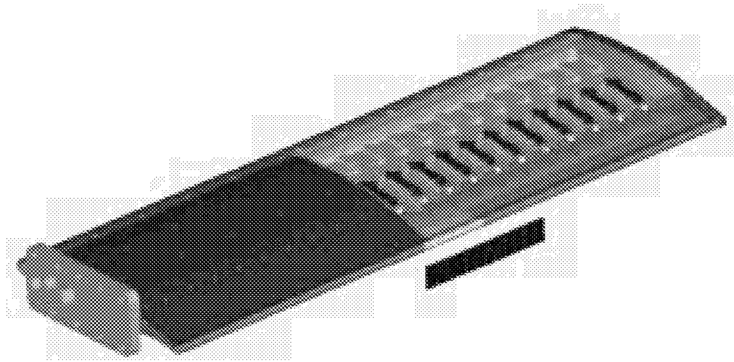
Background Information:
Steady state circulation control has been demonstrated to enhance aerodynamic performance more than 40 years ago; however, mass flow requirements, increased drag and nose down pitching moments have limited its application.

Objective of Current Work:
The objectives of this effort will be to reduce the mass flow requirements by using unsteady flow control. A pneumatic flap system that will minimize drag for application to a general aviation circulation control (GACC) wing will also be designed and evaluated using CFD.

Current Year Accomplishments:
A 2-D flow physics supercritical airfoil model with dual slotted circulation control capability has been designed and built for low speed testing in the LaRC Basic Aerodynamic Research Tunnel (BART). To determine the experimental test matrix and instrumentation requirements, a 2-D CFD effort was used to quantify flow parameters such as boundary layer separation, slot velocity profiles, mass flow, model surface pressure profiles, internal plenum pressures, lift, drag, and pitching moment. The NASA LaRC "**F**undamental **U**nstructured **N**avier Stokes" FUN 2-D code was modified to enable multiple blowing capability. Steady jet calculations were performed over a range of slot heights, blowing rates, and angles of attack. It was found that the use of steady jets, even at very small mass flow rates, yielded a lift coefficient that is comparable or superior to conventional high-lift systems. An example of flow turning and the Coanda effect is shown in figure 1. To design the air supply system the predicted Cm would be limited to 0.2. This would enable the researcher to test through estimated lift coefficients of 4.5 as shown below.

The baseline steady performance of the GACC model is determined with a custom built 5-component balance and will be validated with surface pressures. Predicted pressure distributions highlighted the nose-down pitching moment and movement of the stagnation streamline. These integrated pressure profiles identified specific pitching moment requirements for the balance.





The GACC model (figure 2) has the capability of pulsed blowing using 20 independent actuators placed near the trailing edge slots. These actuators provide a square wave type pressure pulse that can be varied in frequency (5 < Hz < 200), duty cycle, and velocity magnitude (figure 3). Peak magnitudes at the exit of the actuator can be adjusted from zero to sonic conditions. These actuators are based on added mass and can sustain high velocities for large portions of their duty cycle. To quantify the unsteady effects of the pulsed CC conditions, 40 thin films and 13 unsteady pressure transducers are distributed from the upper blowing slot to the to the lower blowing slot. These data will be used to quantify the airfoil system response as well as the time dependent boundary layer separation.

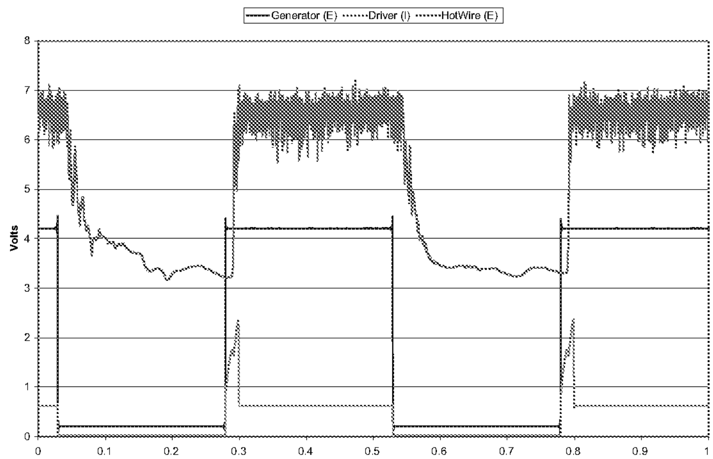


Figure 3

Lessons learned:
Preliminary test results in BART indicate a 40 percent increase in lift at a Cm of 0.02 using pulsed circulation control compared to steady circulation control. Unsteady pressures in the trailing edge were designed for high frequency response, however micro-cracks developed between the wafers and resulted in air leaks into the plenum. The solution: redesign the trailing edge pressure system. The balance was designed for small axial forces resulting in resonant conditions at 12 hertz that dynamically over-ranged the balance at low flow conditions. The solution: stiffen the balance or rebuild the balance with higher load capacity.

Future work:
Leverage off BART test to improve aerodynamic performance. Focus on trailing edge shape, custom blowing along span (i.e., 3-D effects), noise propagation, and pulsed blowing characteristics. Develop FUN-2D code for pulsed circulation control and validate with experimental data.

Formal and informal documentation available:
Abstract submitted for AIAA 1st Flow Control Conference, St. Louis, Missouri, June 2002.

External partners and their accomplishments:
GTRI has completed their wind tunnel test for a pulsed circulation control wing with a fowler type flap. Discussions with Bob Englar indicate that the GTRI siren type actuator did not have the authority to affect the flow. Reports are being written.

Advanced Sensors for Flow Control

Kenneth Wright, 757-864-4665, k.d.wright@larc.nasa.gov
Advanced Measurement and Diagnostics Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

Background Information:
Wall shear stress is an essential parameter in wall-bounded turbulent flows. The information comprised in the shear stress describes the behavior of the flow at the boundary layer, and can be utilized to determine key aerodynamic parameters such as skin friction drag of a surface, transition from laminar to turbulent flow, and flow separation. The total shear stress is comprised of the mean and fluctuating components. The mean component of the shear stress represents the overall behavior of the flow and is used to determine spatial averaged properties like drag. The fluctuating component of the shear stress is an indication of the turbulence associated with the flow. Historically shear stress measurement has been a challenging task with contradictory reports on results from various experiments and researchers. In fact, direct measurement of shear stress has often been considered the “Holy Grail” of experimental fluid dynamics. In addition, the lack of a standard for shear stress calibration adds to the complexity of the problem.

Objective of Current Work:
The objective of the current research effort is to develop techniques to allow high spatial and temporal resolution to be able to accurately measure both components of shear stress. This includes the design, development, and evaluation of direct and indirect methods of measuring shear stress.

Benefits over Existing Systems:
Current shear sensing techniques do not have the high resolution necessary to provide the feedback that is required for actuators in the morphing vehicle of the future.

Previous Work on This Work Package:
In previous years, a 1st generation direct shear sensor was developed and tested with lessons learned incorporated into the design of the current 2nd generation sensor.

Current Year Accomplishments:
The design of the 2nd generation of the direct type shear stress sensor using floating mechanism and backside illumination has been completed.

Completed design of direct shear sensor based on Fiber Bragg Grating embedded in optical fiber.

MEMS indirect shear sensor from University of Florida has been fabricated and initial characterization has been initiated at Langley Research Center.

Lessons Learned:
A multi-disciplinary team needs to be created to develop a systematic method for determining the requirements for shear stress sensors and how to evaluate their performance.

We need to increase the in-house MEMS sensor design capability and leverage external MEMS fabrication facilities in order to improve turnaround time from design concept to delivery of prototype sensor for evaluation.

Future Work:
Shear sensor development team will create a plan for determining performance of various shear stress measurement techniques.

Laboratory evaluation and direct comparison of MEMS indirect shear sensors, direct shear sensors, and traditional shear measurement techniques will be performed by members of the shear sensor development team. A comprehensive report detailing the findings of the team will be completed by the fourth quarter of FY 2002.

External Partners and Their Accomplishments:
The University of Florida is a partner in the fabrication of the 2nd generation floating element shear sensor.

Hampton University has partnered in the design of fiber bragg grating direct shear sensor.

Actuator Development for Micro Aero Adaptive Control (MAAC)

Norman W. Schaeffler, 757-864-5390, n.w.schaeffler@larc.nasa.gov
Flow Physics and Control Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

Background Information:
The potential benefits for active flow have been demonstrated both numerically and experimentally. These benefits may greatly enhance the capability and economical feasibility of air vehicles for a multitude of previously unrealizable scenarios. One of the technical difficulties in this field is related to the actuation necessary to realize the potential of active flow control. At this time the engineering design to build and scale appropriate actuators is mostly an art form. Likewise the interactions between actuation schemes and flow fields to be controlled are not well understood from a fundamental viewpoint.

Objective of Current Work:
The research conducted in this area intends to provide a unified effort for the development and understanding of flow control actuation systems for NASA LaRC research efforts as well as keeping up-to-date on external activities. The results obtained will be used to aid other research efforts actuation design. Multiple actuator types are under investigation including synthetic jets, pulsed jet injectors, low-energy phased plasmas actuators, and high-authority detonation-based injectors. Data are also to be provided for computational fluid dynamic (CFD) validation and modeling efforts from a flow control actuator system view.

Benefits over Existing Systems:
Many flow control actuators schemes are now built on a trial and error basis without any predictive capability of performance. This research will provide basic information to support development of better predictive capabilities. Also, novel actuation schemes are being investigated to improve compactness, simplicity, and authority. Currently actuation authority is a severe limitation to the widespread use of active flow control.

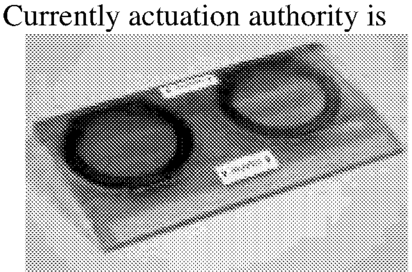


Figure 1. Conformal synthetic jet actuator

Previous Work on This Work Package:
This work package was new in FY 2001. Previous research in the Morphing Project included the development and refinement of piezo-electrically driven synthetic jets.

Current Year Accomplishments:
Piezo-electrically driven zero-net-mass actuators were designed and fabricated using the stereolithography technique to support the Simplified High Lift work package. These actuators were very thin and conformed to the airfoil upper surface as shown in figure 1. The stereolithography material was found to be unacceptable for this application and the actuator degraded severely during the wind tunnel test.

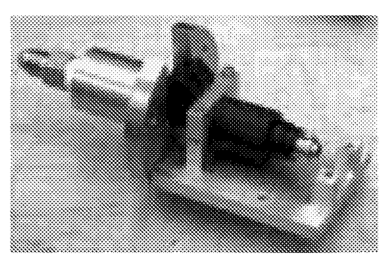


Figure 2. Compressed natural gas fuel injector

COTS compressed natural gas fuel injectors (figure 2) were explored as a possible high power flow control actuator and are currently to be used for 3 projects. Over 30 of these devices were purchased and the electronic circuitry fabricated to operate them. The injector package allows pulsing up to 200 Hz with variable duty cycle and individual injector control. To date they have been used to produce a nearly sonic pulsed jet.

A phased plasma actuator (figure 3) was constructed and demonstrated during the year. In addition, a joint patent was issued to University of Tennessee and NASA LaRC for this technology. The Air Force Office of Scientific Research awarded a grant for the future development phased plasmas for flow control on which NASA LaRC is a partner.

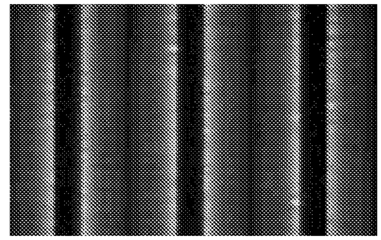


Figure 3. Weakly ionized plasma actuator

To support the modeling and CFD validation efforts, a new synthetic jet actuator was jointly designed by both experimentalists and numericists and fabricated. The input signal, diaphragm motion, cavity pressure and the external flow field are all measured simultaneously. Laser velocimetry and hot-wire measurements have been obtained with Particle Image Velocimetry (PIV) measurements coming soon. CFD predictions are also underway. In addition to the benchmark CFD validation effort, the interaction of synthetic jets with turbulent boundary layers is being studied using PIV. Figure 4 illustrates the effects of the synthetic jet with a round orifice on the flow field in a turbulent cross-flow.

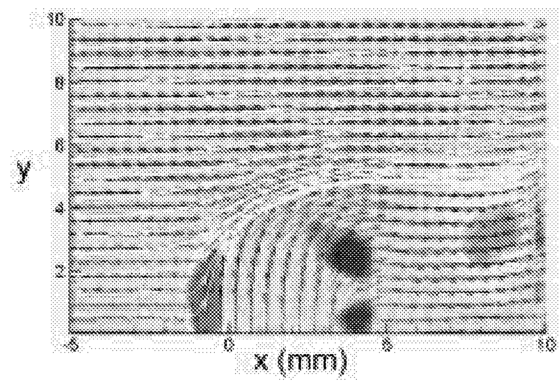


Figure 4. PIV of synthetic jet in Mach 0.1 crossflow

Lessons Learned:
Determined that stereolithography can be an excellent technique to design, prototype and bench test an actuator system. However, the material is not stable or rigid enough for long-term use in actuators with thin parts. Warping of the stereolithography parts can cause actuator failure. Zero-net-mass devices may perform much differently in the flow field to be controlled than on benchtop. Need an indicator of performance during application and better understanding of slot and plenum design needs. Better communication of smart material and power electronic performance requirements for flow control actuators is necessary. The high frequency, high displacement needs for flow control cause unique difficulties.

Future Work:
The research in phased plasmas and detonation-based actuator concepts has been spun off. The physics of the interaction of closely spaced pulsed jets will be studied where phase-shifting the pulses can create a vectoring effect. Further experiments with the purpose of time-accurate CFD validation and modeling are planned. The "Hump" model will be outfitted with a new fast response zero-net mass actuator to provide information for CFD modeling, controls application and to test proper orthogonal decomposition (POD) modeling of separated flows using a space-time correlation. Finally, preparation for investigating the interaction of pulsed supersonic jets in supersonic flow will begin.

Smart Technologies FY 2001 Research Summaries

Electroactive Polymers and Modeling of Electroactive Materials

Joycelyn Harrison, 757-864-4239, j.s.harrison@larc.nasa.gov
Advanced Materials and Processing Branch, Structures and Materials Competency

Background Information:
State-of-the-art piezoelectric and electrostrictive polymers are extremely limited by the degree of strain and force they can exhibit. By developing a two-phase tailorable polymer system, optimization of electromechanical properties via systematic variations of the phases (flexible backbone and polar graft units) can be achieved. Increasing the proportion and polarity of the graft units increases the percent strain output. Increasing the modulus of the backbone enhances the output force capability of the polymer.

Objective of Current Work:
The goals of this research are to develop high performance electroactive polymers for a variety of aerospace sensor and actuator applications and to develop fundamental models to predict characteristic properties of electroactive materials to aid in their application.

Benefits over Existing Systems:
This research seeks to improve the state-of-the-art for electroactive polymers by developing:
1. Electrostrictive polymers with improved force and strain output.
2. Piezoelectric polymers with improved thermal stability, processability, and performance.

Dual functional blends of electrostrictive and piezoelectric polymers that couple sensing and actuation performance.

Previous Work on This Work Package:
Previous work focused only on the development of piezoelectric polyimides. Computational modeling of new piezoelectric polyimide was a major product of previous work.

Lessons Learned:
Completed polymer synthesis, actuator design and characterization. Current actuators exhibit **4 percent strain** and a predicted **output force of 1 N**.

Formal and Informal Documentation Available:
1. Harrison, J. S. and Ounaies, Z.: *Piezoelectric Polymers*. Encyclopedia of Smart Materials, Ed. A. Biderman, John Wiley and Sons, submitted for publication.
2. Su, J., Ounaies, Z., Harrison, J. S., Bar-Cohen, Y., and Leary, S.: *Electromechanically Active Polymer Blends for Actuation*. Proceedings of SPIE-Smart Structures and Materials, Vol. 3987, pp. 65-72, 2000.
3. Su, J., Ounaies, Z., and Harrison, J. S.: *Ferroelectric and Piezoelectric Properties of Blends of Polyvinylidene-trifluoroethylene and Graft Elastomer*. Proceedings of MRS Fall Meeting, Vol. 600, 2000.
4. Su, J., Harrison, J. S., St. Clair, T., Bar-Cohen, Y., and Leary, S.: *Electrostrictive Graft Elastomers and Applications*. Proceedings of MRS Fall Meeting, Vol. 600, 2000.
5. Su, J., Costen, R., and Harrison, J. S.: *Design and Fabrication of Bending Actuators Using Electrostrictive Graft Elastomers*. Proceedings of SPIE Smart Structures and Materials, 2001.

6. Su, J., Harrison, J. S., and St. Clair, T.: *Novel Polymeric Elastomers for Actuation*. Proceedings of IEEE International Symposium on Application of Ferroelectrics, 2001.

Patents Disclosures Submitted
1. Electrostrictive Graft Elastomers and Processing--LAR 16038-1.
2. Electrostrictive Polymer-Polymer Bilyaer Actuator--LAR 15960-1.
3. Piezoelectric and Electrostrictive Polymers for Sensor-Actuator Dual Functionality—LAR 16232-1.

External Partners and Their Accomplishments:
North Carolina State University - Dr. Ralph Smith

Flex Circuits and Cables

Kevin N. Barnes, 757-864-6686, k.n.barnes@larc.nasa.gov
Systems Integration Branch, Airborne Systems Competency

Background Information:
Circuit substrate technology has moved from the traditional flat rigid boards to flexible substrates and rigid-flex boards, a hybrid of the rigid and flexible technologies. Presently, flexible substrates are made from sheets of polyimide (Kapton) laminated with adhesives to copper foil traces, to other layers that afford a multilayer substrate that are employed in circuits for cell phones, cameras, laptop computers, touch pads, and instrument clusters. The main driver that moves this work package is to step ahead of the traditional technology and employ thermoplastic polyimide films thereby eliminating the problems of delamination prone to the traditional technology. Future efforts will focus on the embedded active and passive devices as well as moving in the direction of plastic transistors and integrated circuit.

Objective of Current Work:
The objective of this Work Package (WP) is to investigate and develop Flexible Multilayer Circuits and Flexible Cables for aerospace applications utilizing a flexible thin film polyimide insulating material known as LaRC™ -SI. Upon completion of this effort, systems will be fabricated to facilitate work packages under Biologically-Inspired Flight Systems, Micro-Aero Adaptive Control, Smart Technologies, and Adaptive Structural Morphing project technologies that require flexible printed circuits/cables that can be employed with MicroElectroMechanical systems and MultiChip Modules, presently being developed under other Morphing work packages.

Benefits Over Existing Systems:
This technology can cover broad applications in aerospace systems that require efficient lightweight electrical/electronics systems deigned for constrained areas, adhesion to complex surfaces, and embedding within composite materials. Continual application of this research and technology has been driven by the needs of several LaRC programs and spin-off applications.

Previous Work on this Work Package:
Last year's accomplishments included work in areas of: multilayer film lamination and examination; enhancements to the Microelectronics Fabrication Facility Film-Casting and Circuits Lay-Up laboratories; Chip-on-Flex and Die-on Flex demonstrations; circuits with shields, ground and power planes; CAE, CAD and CAM implementation; Flex Cable embedding; minor success with punched, plasma etched micro-drilled vias; and employment into applications such as the Buffet F-18 composite vertical tail section, Micro-UAC and UAV flyers. In addition, a contract with Integral Wave Technologies was started to demonstrate embedding passive devices.

Current Year Accomplishments:
For FY 2002, activities and efforts have been driven by the needs and negotiations of other work packages in Morphing. However, there still remains a continuing and ongoing FY 2001 effort in the areas of multilayer bonding, flex circuit fabrication of design prototypes, researching ways to overcome limitations.

Lessons Learned:
Some of the key lessons learned included additional research needed in areas of multilayer lamination, laboratory enhancements, and the limited availability of integrated circuits (ICs) in Die and Flip-Chip packages. Understanding the limitation of punched, plasma etched, and micro-drilled vias has driven the need to investigate alternative via fabrication methods. Laser Ablation systems are presently under review and are highly needed to continue to move this technology in a successful direction. Other lessons include the high-market capability this technology has shown, primarily driven by the needs of LaRC Program applications.

Future Work:
To continue to remain proactive in providing flex circuits for other LaRC activities including microflyers, aircraft noise abatement, and working with other engineers and technicians in the design of electronic circuits that support active wing and structures activities. Future activities will include a continuation of the above, finalizing the film bonding experiment, and the integration of the microflyer data logger to a GPS navigation system. Long-term interest also includes the employment of organic or plastic transistors in suitable flexible multilayer circuit applications. Employment of the flex circuit technology with Chips-on-Board, Chips-on-Structures, Die-on-Flex, and Micro-Chip-Modules will continue to be a strong motivator and research interest.

Formal and Informal Documentation Available:
Presently there is no formal documentation. However, groundwork is in place for reporting on subjects in the areas of Multilayer Circuits, Signal Transmission, Flexible Substrates, Thick Film Active and Passive Devices, and the employment of Flex Circuits and Cables into LaRC applications.

External Partners and Their Accomplishments:
A contract with Integral Wave Technologies has been started to develop methods for fabricating integrated passive components (resistor, capacitors, and inductors), embedding passive components in flexible printed circuit boards, and demonstrating a process for embedding and electrically connecting thinned integrated circuits (ICs)—active components (transistors, diodes). This effort will then move to developing methods of integrating the above for fabricating high-density electronic printed circuit boards using the LaRC-SI polyimide material. Conversations have also begun with Johns Hopkins Applied Physics Lab for a similar activity.

The following services are provided to other work packages in the Morphing Project:
1. Integration of a Data Logger on a Flex Circuit substrate to micro fliers: Developed/coordinated by Martin Waszak of RDB/Dynamics & Control Branch, AirSC.
2. Data Logger will also be integrated with a GPS chip that was purchased by Qamar Shams of RBM/Instrumentation Systems Development Branch, AAAC.

In addition to the above, other WP partnerships continue to be ongoing with LaRC researchers: D. L. Palumbo, E.G. Cooper, and M. J. Logan, Q.A. Shams, R.H. Cabell, and M.A. Kegerise. Support from their program managers and the technical staff under Systems Engineering Competency continues to be a key element to the success of this effort.

Microwave-driven Smart Membrane Actuators

Sang H. Choi, 757-864-1408, s.h.choi@larc.nasa.gov
Advanced Materials and Processing Branch, Structures and Materials Competency

Background Information:
The most state-of-the-art actuator smart materials still require driving voltages from several hundred to thousand volts. Most current power supplies are bulky and heavyweight. The wired mesh network for actuator array is complex and a weight-adding factor and causes cross-coupling among wires. There are few immediate solutions available in the foreseeable future by conventional approaches.

Objective of Current Work:
To develop rectenna array-based microwave power driven actuator systems that are wireless and simple and provide sufficient driving voltages.

Benefits over Existing Systems:
High voltage power supply, power storable, lightweight and less complex (no wire network, so cross-talk), thin-film technology, and power allocation and distribution possible.

Previous Work on this Work Package:
Patch rectennas (70 volts output) were developed jointly with Jet Propulsion Lab (JPL). Breadboard level (4x4 array) of a PAD logic circuit was developed. A test with a piezoelectric actuator (multilayers) was done.

Current Year Accomplishments: (see the bottom figures too)
1. High voltage patch rectenna (designed with 540 volts and tested with > 200 volts) was developed.
2. An 8x8 breadboard level PAD logic circuit was developed.
3. Demonstration of THUNDER actuator with a patch rectenna was made successfully.

Lessons Learned:
1. Sufficient beaming power will be required to compensate the power loss due to incident angle change by changing actuator plane.
2. Power storage of surplus beam power is much efficient for optimal operation.
3. Development of dipole rectennas is necessary to meet high power density and flexibility of membrane structures.

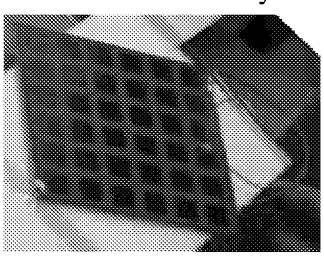
Future Work:
1. High voltage requirements of actuator smart materials will drive development of high voltage hold-off Schottky barrier diodes and MOSFETs using GaN or SiN.
2. Design and fabrication of dipole rectennas.
3. Printed circuit board (PCB) of PAD logic circuit with power storage concept.

Formal and Informal Documentation Available:
1. Choi, S. H., Chu, S. H., Kwak, M., and Cutler, A. D. *Microwave-driven Smart Material Actuators*. Proceedings of SPIE - Smart Structures and Integrated Systems, Vol. 3668, Part-2, p.853, March 1999.

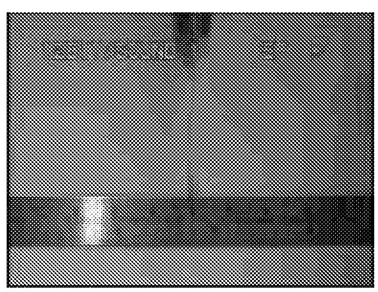
2. Chu, Sang-Hyon, Choi, Sang H., Mia Kwak, Cutler, Andrew D. and Song, Kyo D. *Smart Material Actuator driven by Networked Rectenna Array*. Proceedings of 34th IECEC, Paper 1999-01-2646, CD-ROM Format, Vancouver, Canada, August 2-5, 1999.
3. Choi, Sang H., Golembiewski. Walter T., Song, Kyo D. Song. *Networked Rectenna Array for Smart Material Actuators*. Proceedings of 35th IECEC, AIAA 2000-3066, Las Vegas, Nevada, July 31-August 3, 2000.
4. Song, Kyo D., Golembiewski. Walter T., and Choi, Sang H. *Design of Power Allocation and Distribution Circuit with Rectenna Array for Smart Material Actuators*. Proceedings of International Symposium on Smart Structures and Microsystems 2000, Hong Kong, October 19-21, 2000.
5. Choi, Sang, Golembiewski. Walter T., Song, Kyo D., and Bryant, Robert G. *Networked Rectenna Array with Power Allocation and Distribution Circuit for Smart Material Actuators*. SPIE's 8th International Symposium on Smart Structures and Materials, Newport Beach, California, Vol. 4334, pp. 372-381, March 4-8, 2001.

Invention Disclosures:
1. Choi, Sang H., Lake, Mark S., and Moore, Christopher. *Microwave-driven Smart Material Actuators*. Invention Disclosure, NASA Case No. LAR 15754-1, September 24, 1998.
2. Choi, Sang H., Golembiewski. Walter T., and Song, Kyo D. *Networked Array Circuitry for Power Allocation and Distribution (PAD)*. Invention Disclosure, NASA Case No. LAR-16136-1-CU, July 31, 2000.
3. Choi, Sang H. *Microwave Rectenna based Planarity Monitoring Sensor*. Invention Disclosure, NASA Case No. LAR 16221-1, October 18, 2000.

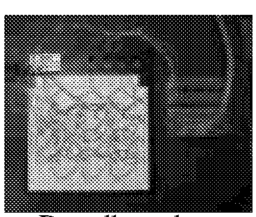
External Partners and Their Accomplishments:
JPL: Design and fabrication of two patch rectennas for the output voltage of > 200 volts.
Norfolk State University: Test of rectenna and design of PAD logic circuit.



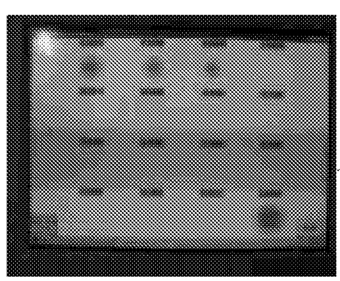
Currently Achieved:
- 6 x 6 arrays
  Max 540 volts
- 7.5 V Schottky diode (GaAs)



Electroactive paper
Voltage: 50 volts
- Length: 30 mm
- Width: 10 mm
- Thickness: 24.5 mm
- Displacement: 3.2mm



Breadboard



PAD Logic Circuit
Power levels controlled by a PAD logic circuit appear in a size of red-colored dots

Performance Characterization and Design Optimization of Macro-Fiber Composite Actuators

Dr. W. Keats Wilkie, 757-864-1260, w.k.wilkie@larc.nasa.gov
Structural Dynamics Branch, Structures and Materials Competency

Background Information:
Piezoceramic devices operating in a d_{33} mode generate the greatest work-energy for a given actuator mass. In general, a factor of four increase in work energy density over the d_{31} mode of operation is to be expected. However, manufacturing a practical d_{33} device suitable for distributed use in a structure has proven to be extremely difficult. The Langley Macro-Fiber Composite actuator (MFC) is the first reliable and *manufacturable* distributed d_{33} actuator device to be successfully produced. Prototype MFC's have been used in a number of applications, even though high fidelity performance characterization and reliability data were not yet available. Precise determination of the design sensitivities of the MFC geometry, which in principal would allow optimization of the MFC device, has also been unavailable.

Objective of Current Work:
1. Experimentally, and rigorously, characterize the fundamental performance properties of baseline MFC device.
2. Determine sensitivities in MFC performance to variations in interdigitated electrode spacing and ceramic thickness.
3. Develop and characterize improved ("optimized") MFC device based on design sensitivity data.

Benefits over Existing Systems:
1. Factor of two increase in maximum output work energy density over best available alternative d_{33} device (C3 AFC).
2. Factor of four energy density improvement over best conventional d_{31} devices (ACX QuickPak, NASA FlexPatch).
3. Factor of four improvement in strain-per-volt output over best alternative d_{33} device.
4. Order-of-magnitude reduction in unit fabrication cost over best alternative d_{33} device.

Previous Work on this Work Package:
Successfully developed baseline MFC concept and manufacturing processes, and demonstrated MFC performance in realistic applications (FY98.5-FY00).

Current Year Accomplishments:
1. Developed and characterized optimized MFC package.
   - Doubled strain-per-volt output of baseline MFC.
   - Incorporated high performance packaging materials.
2. Determined/defined fundamental engineering properties of MFC device.
   - Elastic moduli, orthotropic actuator laminate properties.
   - Package strength.
   - Actuation frequency response.

3. Developed, proven repeatable manufacturing process.
   - 95% yield.
   - <5% variation in package-package performance.
4. Demonstrated high-lifecycle endurance and reliability.
   - Endurance exceeding 10^8 cycles for normal operation.
   - Endurance exceeding 10^7 cycles for extreme operation.

Lessons Learned:
1. MFC strain output scaled *linearly* with electric field over range tested (21 mil to 63 mil).
   - Permitted design of lower voltage device with same performance (MFC2)
2. No strong variation in performance with ceramic thickness observed over range tested (5 mil to 9 mil).
   - Caution to be advised if extrapolating outside of thickness/IDE spacing aspect ratios tested here.
3. Mechanical properties MFC devices adequately predicted using simple rules-of-mixtures micromechanics models.
   - Micromechanics predictions within 10% of (limited) experimental measurements.
4. Manufacturing process highly reliable and repeatable
   - Must adhere to reasonable quality control measures however!

Future Work:
1. Some *ad hoc* experiments with ultrafine IDE spacing currently underway (non-Morphing funded).
2. Some package endurance testing to occur in FY 2002 (non-Morphing funded).
3. *No fundamental research issues remaining for MFC technology*.
   - MFC recognized as TRL 6.
   - Future work expected to be driven by application specific requirements. (Should be application program funded.)

Formal and Informal Documentation Available:
1. Wilkie, W. K., R. G. Bryant, J. W. High, R. L. Fox, R. F. Hellbaum, A. Jalink, Jr., B. D. Little and P. H. Mirick. *Low-Cost Piezoelectric Actuator for Structural Control Applications*. Proceedings of the SPIE, Smart Structures and Materials 2000 - Industrial and Commercial Applications of Smart Structures Technologies, (3991), 323, (2000).
2. Wilkie, W. Keats, High, James W. *Design, Fabrication and Characterization of a Conformable, High-Performance Anisotropic Piezoelectric Composite Device for Structural Control Applications*. NASA TM, draft in progress, December 2001.

External Partners and Their Accomplishments:
Carlos Cesnik, MIT (and University of Michigan)
   - Performed stress strain and strength tests of MFC devices.
   - Investigated use of MFC devices for optimizing torsinal deflection control in thin-walled closed section composite tubes.

Dan Inman, Virginia Tech
   - Investigated MFC devices for distributed vibration sensing on toroidal inflatable spacecraft structures.

MDO Techniques and Novel Aircraft Control Systems

Sharon L. Padula, 757-864-2807, s.l.padula@larc.nasa.gov
Multidisciplinary Optimization Branch, Aerospace Systems, Concepts & Analysis Competency

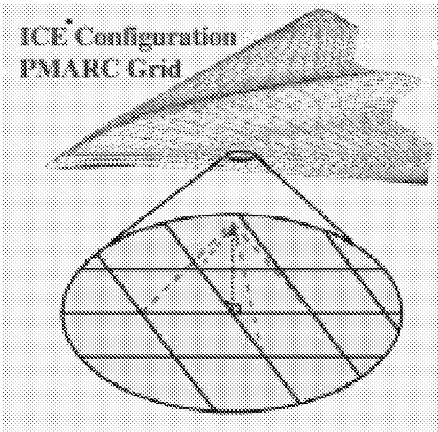
Background Information:
In order to adapt to diverse mission scenarios, military aircraft need a stealthy maneuvering capability. One option being considered is the use of synthetic jets - zero-mass flow devices activated by vibrating membranes. These devices can provide virtual shape change of aerodynamic surfaces thus producing control moments. This research develops preliminary design methods that estimate and enhance the effectiveness of synthetic jets through fast aerodynamic reanalysis and optimal actuator placement.

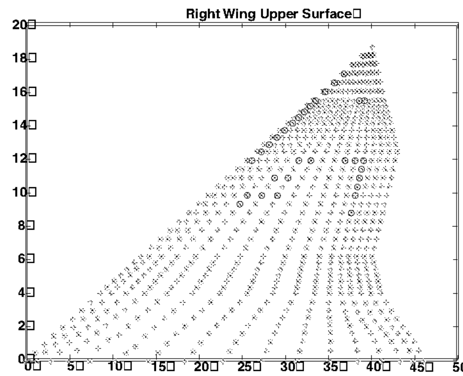
Objective of Current Work:
To develop methods for design of novel aircraft control systems, especially those with large numbers of synthetic jet effectors rather than conventional flaps.

Benefits over Existing Systems:
These innovative control system concepts enable new mission scenarios by reducing both airframe noise and radar cross-section. This approach is applicable to revolutionary aircraft concepts for which a computational fluid dynamics (CFD) model exists.

Previous Work on This Work Package:
The approach is demonstrated on the Lockheed Martin Innovative Control Effector (ICE) model shown in the figure. Given a low fidelity model of the ICE configuration, the process consists of three steps. First, use automatic differentiation of the PMARC CFD code to predict the change in pitch, roll and yaw moments with respect to a shape change in any single effector. The predicted sensitivity derivatives are used to produce six color contour plots of control effectiveness. Second, study the contour plots and identify a subset of 350 candidate locations. Use the sensitivity derivatives plus an estimate of the maximum attainable shape change to predict the global pitch, roll and yaw moments for any combination of multiple effectors. Third, use a genetic algorithm (GA) to find the best set from the 350 candidate locations.

Current Year Accomplishments:
The goal is to minimize the number of effectors required to complete all maneuvers specified by the controls expert. One excellent set of effectors is illustrated in the figure. The shaded dots indicate single effector locations for which sensitivity derivatives are available. The black circles indicate the selected locations on the upper surface of the right wing. The GA evaluated 150,000 combinations of effectors out of about 3×10^{99} possible combinations. This approach provides the controls expert with promising designs for further evaluation.





Lessons Learned:
Existing, low-order CFD codes such as PMARC and A502 can be adapted to model synthetic jet effectors. These linear aerodynamic panel methods are inappropriate for detailed study of the flow field but provide quick estimates of control moments. This study concludes that additional analytical modeling and experimental testing of synthetic jets are needed to improve design confidence.

Future Work:
The code A502 is an aerodynamic panel method similar to PMARC that is used by NASA and by industry. A fast reanalysis capability will be added to A502 and both codes will be compared with high fidelity CFD codes and with experimental results in order to enhance our ability to model synthetic jet effectors.

Formal and Informal Documentation Available:

1. Padula, Sharon L., Rogers, James L., and Raney, David L. *MDO Techniques and Novel Aircraft Control Systems*. AIAA Paper No. 2000-4848.
2. Cook, Andrea M. and Crossley, William A. *Investigation of GA Approaches for Smart Actuator Placement for Aircraft Maneuvering*. 39th AIAA Aerospace Sciences Meeting, January 2001, Reno, Nevada.
3. Cook, Andrea M. *Genetic Algorithm Approaches to Optimizing the Location and Number of Smart Actuators on an Aircraft Wing*. Master's Thesis, Purdue University, December 2000.

External Partners and Their Accomplishments:
A Purdue University grant supported one student and produced a modified version of PMARC that predicts plausible control moments and is three times faster than the original. To exercise and test the new version, a GA was applied to the design of an unmanned air vehicle (UAV) concept. The GA successfully identified a set of nine synthetic jet effectors needed for control. The GA-based method found several feasible effector placement designs that were compared with conventional UAV designs completed by Purdue senior design class students.

Flight Control Technologies for Adaptive Aerospace Vehicles

Dave Raney, 757-864-4033, d.l.raney@larc.nasa.gov
Dynamics and Control Branch, Airborne Systems Competency

Background:
Recent discoveries in material science and fluidics have been used to create a variety of shape-change and fluidic effector devices that offer the potential to enable new approaches to aerospace vehicle flight control. Future aerospace vehicles might use distributed arrays of hundreds of such devices for stabilization and maneuver control, thereby augmenting or replacing conventional ailerons, flaps or rudders. Although several research efforts at universities, government labs and industry are underway to develop and characterize these devices, few activities address the incorporation of such arrays into aerospace vehicle flight control architectures.

Objective & Approach:
This research seeks to develop flight control concepts for adaptive aerospace vehicles that utilize flow measurements from distributed sensor arrays and issue commands to large numbers of distributed effectors to achieve a desired control objective. Such control objectives include active separation control, stabilization and maneuver control, disturbance rejection or upset recovery, mission-adaptive performance enhancement, and failure accommodation. Control algorithms are developed and evaluated using computer simulation models, wind tunnel tests, and unmanned aerial vehicles (UAVs). The research also supports various closed-loop experiments being performed in the Morphing program.

Benefits:
In addition to the aforementioned control objectives, reduced fuel consumption, enhanced maneuverability, reconfigurability, failure tolerance and mission adaptability are potential benefits of distributed effector and sensor arrays.

Previous Work:
Prior work has focused on placement and control design for an aircraft equipped with distributed surface "bump" effectors.[1-4] The simulation showed that such devices offered promise for seamless aircraft flight control. Previous efforts also provided control support for an active separation control wind-tunnel experiment in Langley's 0.3m cryogenic wind tunnel.[5]

Accomplishments & Lessons Learned:
Currently, research is focusing on the use of a highly instrumented UAV as a testbed for the development of flight control algorithms using distributed shape-change actuator and pressure sensor arrays. The UAV shown in figure 1 is a delta planform operated by North Carolina State University under a cooperative agreement with NASA. Also shown in figure 1 is a panel model of the vehicle that was used to create a dynamic simulation for preliminary control law development.

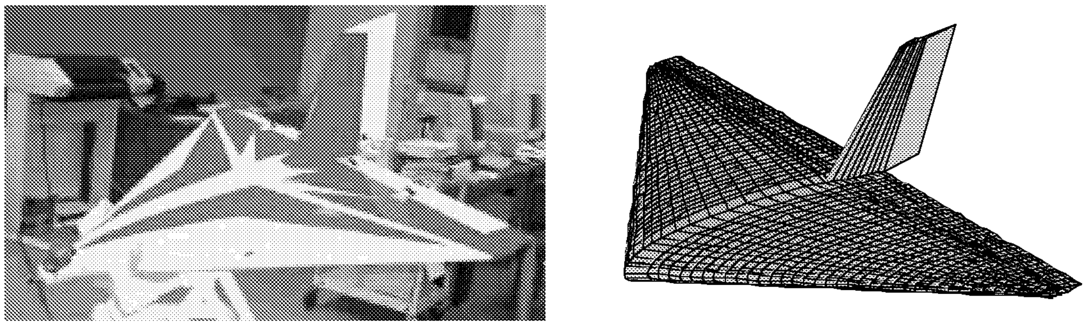


Figure 1. Shape-change UAV and panel model used to develop dynamic simulation.

The vehicle is equipped with an array of 18 trailing-edge shape change effector segments on each wing. Distributed pressure measurements and off-the-shelf control processors are associated with each independently controlled shape-change segment (figure 2). The flight control system also includes a central processor with access to air data, inertial measurements and GPS. This flexible control architecture provides the ability to evaluate a wide variety of centralized and decentralized control algorithms in the presence of real-world uncertainties and under various failure scenarios.

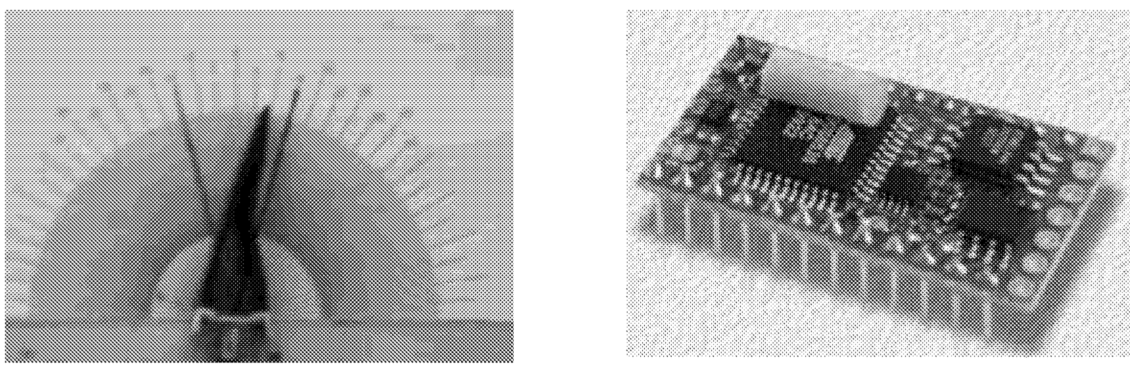


Figure 2. Shape-change effector segment and associated controller chip.

Control algorithms that use the shape-change effector and pressure sensor arrays are currently under development. Accomplishments during FY 2001 included the initiation of the cooperative agreement with NC State, downselect of the UAV testbed, selection and preliminary development of the actuation concept, and creation of modeling tools and dynamic simulations of the UAV for control algorithm development. Preliminary evaluations of control authority were conducted using these modeling tools, and the resulting control effector models were incorporated into the dynamic simulation of the UAV. A baseline control algorithm was implemented in the simulation that uses the shape-change effector array to stabilize and maneuver the UAV. Closed loop eigenvalues and 20-degree roll doublet maneuver time histories from the simulation are shown in figure 3. The rolling maneuver was simulated in still air (solid line) and severe turbulence (dashed line). Actuator bandwidth and deflection requirements are being generated from the simulation. Development of the UAV control architecture, sensor and actuator systems is still under way.

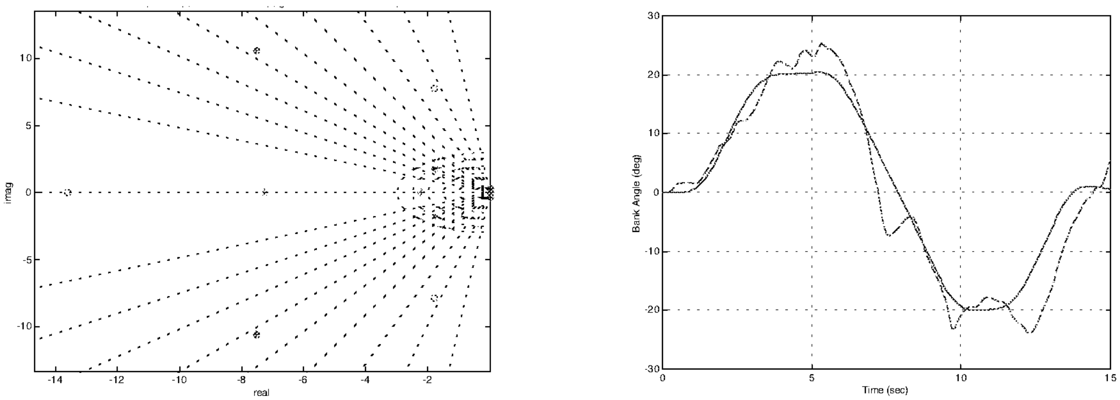


Figure 3. Closed-loop UAV simulation eigenvalues and rolling maneuver time history.

Documentation/References:

1. Raney, D. L., Montgomery, R. C., Green, L. L. and Park, M. A. *Flight Control using Distributed Shape-Change Effector Arrays*. AIAA Paper 2000-1560, April 2000.
2. Scott, M. A., Montgomery, R. C. and Weston, R. P. *Subsonic Maneuvering Effectiveness of High Performance Aircraft which Employ Quasi-Static Shape Change Devices*. Proceedings of the SPIE - Smart Structures and Materials, Vol. 3326, pp. 223-233, 1998.
3. Park, Michael A.; Green, Lawrence L.; Montgomery, Raymond C.; Raney, David L. *Determination of Stability and Control Derivatives Using Computational Fluid Dynamics and Automatic Differentiation*. AIAA Paper No. 99-3136. 17th Applied Aerodynamics Conference, June 1999.
4. Padula, Sharon L.; Rogers, James L.; Raney, David L. *Multidisciplinary Techniques and Novel Aircraft Control Systems*. AIAA Paper No. 2000-4848.
5. Allan, Brian G.; Juang, Jer-Nan; Raney, David L.; Seifert, A.; Pack, Latunia G.; Brown, Donald E. *Closed-Loop Separation Control using Oscillatory Flow Excitation*. ICASE Report 2000-32.

Adaptive Structural Morphing FY 2001 Research Summaries

Biomimetics Ways To Create Efficient Multifunctional Structures

Dawn Jegley, 757-864-3185, d.c.jegley@larc.nasa.gov
Mechanics and Durability Branch, Structures and Materials Competency

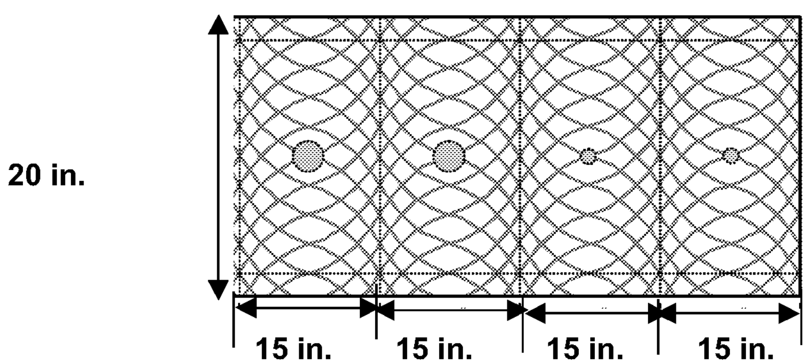
Background Information:
In nature, structures perform a variety of different functions in addition to carrying load. The objective of this effort is to design structures that are capable of performing multiple roles such as carrying load and monitoring behavior or damage in an efficient manner.

Objective of Current Work:
Design and test curvilinear fiber panels then evaluate data from flat panels with central cutouts to design more structurally efficient and complex panels. At the same time, examine fiber optic strain results to improve the fiber optic package to allow fiber optics to be integrated into the panel.

Benefits over Existing Systems:
Curvilinear panels will allow for more efficient, and therefore, lighter structures. Joining fiber optics with the improved efficiency will allow for health monitoring to reduce inspection costs and strain measurements to improve testing capabilities. These factors could apply to numerous concepts where holes are needed (spar-rib joints, for example) or where strain monitoring would be of value.

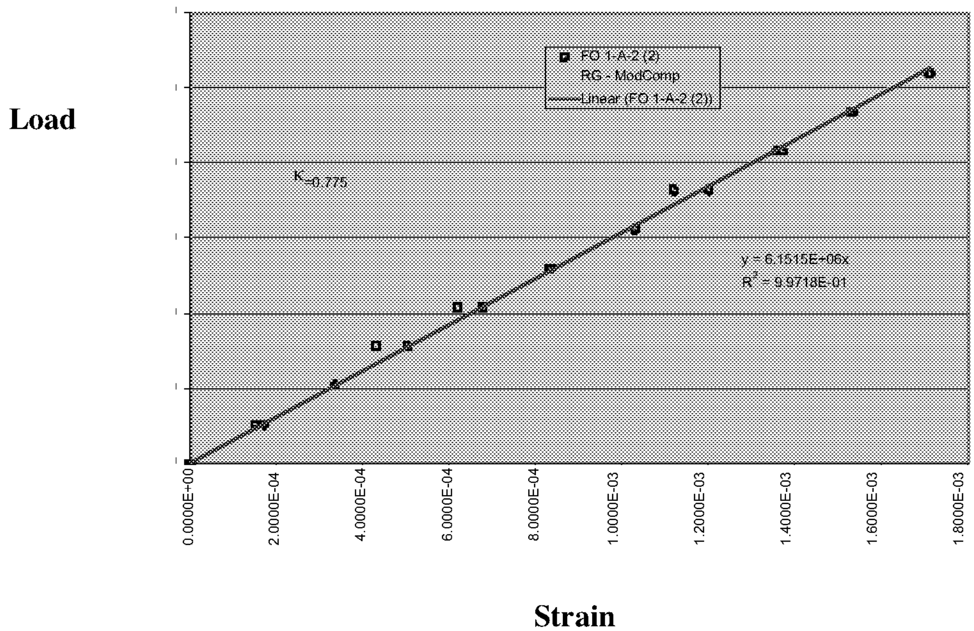
Previous Work on this Work Package:
Preliminary design work to establish potential of the curvilinear fiber idea.

Current Year Accomplishments:
A parametric study of stacking sequences was used to determine best design. Results indicate that using curvilinear fibers can increase the buckling load by up to 50 percent for panels with holes. Designs were completed for curvilinear panels with and without holes. Twelve panels were fabricated and prepared for testing. Additional panels that are cured but not cut into specimens are to be tested after evaluation of the results from the first series.



Curvilinear fiber pattern

Fiber optic tests of aluminum panels were completed. Fiber optic data points are not as consistent as conventional gages but averages to the same values as conventional gages.



Strains determined by fiber optics and by conventional gages.

Lessons Learned:
Shifting the tows of material when graphite panels are constructed reduces the tendency to warp during and after curing. Quality control must be improved on the fiber optic wires.

Future Work:
Curvilinear fiber panel testing in compression is to be completed in FY 2002. Integration of curvilinear fibers and fiber optics will continue. Analysis of the wire itself (coatings, adhesive, etc.) will be initiated.

External Partners and Their Accomplishments:
Adoptech Inc., designed the curvilinear panels and Cincinnati Machine fabricated them.

Adaptive Wing Structural Concepts

Tom Jordan, 757-874-4713, t.l.jordan@larc.nasa.gov
Model Systems Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

Background Information:
Birds, bats, and marine creatures have demonstrated the ability of a single system to achieve multiple tasks through the ability to drastically change shape. Although adaptive wing structures and multipoint design have been demonstrated in aircraft through the use of high lift systems, aeroelastic tailoring, variable sweep, and other methods; it is believed that new methods for wing shape change that mimic biological structures can be achieved using recent advances in materials, smart actuators, electronics, and control systems.

Objective of Current Work:
The objectives of the current work include:
1. Develop novel structural concepts for wings and other lifting surfaces that provide multipoint efficiency without traditional hinged surfaces.
2. Investigate emerging technologies in smart actuators, sensors, MEMS, and associated electronics for use on new wings with non-traditional control surfaces.
3. Investigate and develop flexible and segmented surfaces to act as wing coverings that require significant dimensional change.
4. Investigate fabrication techniques for all the above electrical and mechanical hardware.
5. Coordinate with other groups within LaRC to target aerodynamically high-payoff configurations for a given missions.

Benefits over Existing Systems:
Previous work in this area has been focused on relatively small changes to the leading and trailing edges of wing surfaces. This work will develop aerodynamic surfaces with large structural changes and incorporate the enabling hardware and electronics.

Previous Work on this Work Package:
The Adaptive Wing Concepts work package started in 2001.

Current Year Accomplishments:
A team within the Model Systems Branch was formed. The team generated 14 concepts that could provide desired shape changes. These concepts were ranked and three concepts were designed from the ranked concept list; two of the concepts were fabricated. The Fishbone Wing was designed by MSB personnel and fabricated in-house. A PC-based system was developed which controls the shape of the wing. The other demonstrator was designed and fabricated by Advanced Technologies Inc (ATI), and delivered to MSB personnel in September of 2001. Enabling technologies such as flexible or segmented skins were identified and require development for future progress.

Lessons Learned:
1. Elastic, pliable, and segmented skins are key elements for many conceptual designs.
2. Currently available smart actuators are still behind conventional actuation systems as far as stroke, force, frequency response, and operational lifetime. However, there is much research in this area, which will likely provide new smart actuators that are ideal for some

applications. Wind tunnel models and demonstrators that utilize smart materials and smart actuators require extensive amounts of electrical hardware for support. Miniaturization of electrical hardware will be required for use on flight vehicles.

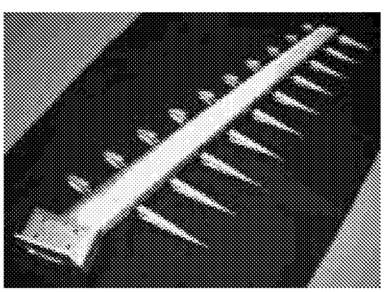
3. Actuation systems must work in concert with the wing structure to achieve the desired shapes. This requires the development of concepts where structural stiffness is dynamically controlled. The structure should only be stiff enough to resist flutter for the desired flight conditions.
4. Wind tunnel testing will require mechanical hardware, actuators, instrumentation, and skins with much greater complexity than those used on current wind tunnel tests. More in-depth, structural/dynamic analysis will be required to meet safety standards for testing of morphing wind tunnel models. New methods of measurement for quantifying surface deflection of aerodynamic surfaces need to be developed.

Future Work:
Future work will be to:

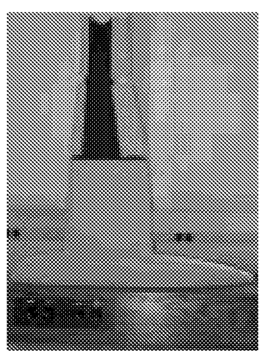
1. Continue all current work described above.
2. Investigate and develop methods to obtain 3-D surface contour for flexible structures undergoing wind tunnel testing.
3. Integrate structural design and sensor/actuator technology for wind tunnel and R/C models.
4. Perform kinematic analysis, structural analysis, and aerodynamic payoff for all existing and subsequent concepts. MSB and other groups will perform these analyzes.

Formal and Informal Documentation Available:
Contract report for ATI demonstrator, model # RBL-01-0183.
Contract report for DEI demonstrator, model # RBL-01-0184.

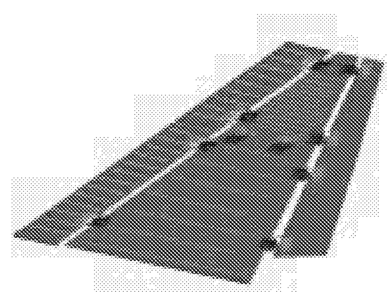
External Partners and Their Accomplishments:
Advanced Technologies Inc., designed and fabricated a model that demonstrates large changes in wing tip deflection. Dynamic Engineering Inc., (DEI) designed a demonstrator model that incorporates Shape Memory Alloy (SMA) actuators to achieve structural morphing objectives. This model was designed but not fabricated.



Fishbone Demonstrator



ATI Demonstrator



Adaptive Aeroelastic Demonstrator (DEI)

High-Rate, Morphable, Hingeless Control Surface Demonstrated in the TDT

Jennifer Pinkerton Florance, 757-864-1230, j.p.florance@larc.nasa.gov
Aeroelasticity Branch, Structures and Materials Competency

Background Information:
Typically, aircraft wings are designed to be most efficient at a single flight condition but suffer performance penalties at other flight conditions. Historically, these penalties have been reduced through the judicious deflection of "conventional" leading- and trailing-edge hinged control surfaces. Since the 1980's, many researchers have investigated the use of fully-integrated adaptive material actuator systems (so called "smart technologies") for performance-enhancing shape control. These devices are promising because they offer a significant advantage over their conventional counterparts: no flow-disturbing hingelines. The DARPA/AFRL/NASA/Northrop Grumman Smart Wing program was one such effort addressing the development and demonstration of smart technologies.

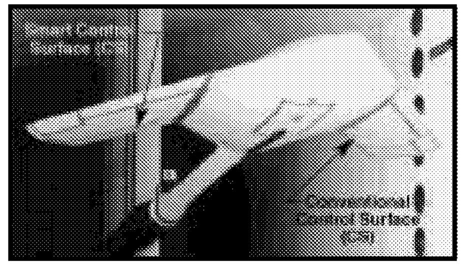
Objective of Current Work:
The overall objective of the Smart Wing program was to develop smart technologies and demonstrate novel actuation systems to improve the aerodynamic and aeroelastic performance of military aircraft. The FY 2001 wind-tunnel test in the Transonic Dynamics Tunnel (TDT) focused on demonstrating realistic actuation rates of a hingeless, smoothly contoured, "smart" trailing-edge control surface while maintaining or improving the aerodynamic performance benefits demonstrated during previous Smart Wing TDT entries.

Benefits over Existing Systems:
The results of the Smart Wing program have laid the ground work for developing smart control effectors that can provide an alternative and potentially more effective means of achieving aerodynamic and aeroelastic control while improving the low observable characteristics of future air and space vehicles, particularly if considered early in the design cycle. Issues related to power supplies, cost, system reliability, and overall system integration must still be overcome, but the demonstration of high-actuation-rate, hingeless, smoothly contoured control surfaces with both chordwise and spanwise shape variability are a significant milestone in the development and application of smart technologies.

Previous Work on this Work Package:
The Smart Wing program began in 1995 and was comprised of two phases. In Phase 1, which ended in February 1999, two 16 percent geometric-scale semi-span models of an advanced military aircraft wing, one with hingeless nickel-titanium (NiTi) shape-memory-alloy (SMA) trailing-edge smart control surfaces and a central torque tube (to provide wing twist) and the other with conventional trailing-edge control surfaces, were tested twice in the TDT. During the tests, a maximum of 5 degrees of wing twist was achieved using the SMA torque tube concept, resulting in an approximate 15 percent increase in rolling moment and 11 percent increase in lift relative to the untwisted conventional wing. The SMA control surfaces were deployed up to 10 degrees, with the hingeless ones providing (1) an approximate 10 percent improvement in lift and rolling moment for independent control surface actuation (flap and aileron alone, respectively) and (2) a 15-17 percent improvement in lift and rolling moment for combined

deployment. Phase 2 of the program began in January 1997 and utilized a sting-mounted, full-span, 30 percent geometric-scale, flexible model based on the Northrop Grumman Unmanned Combat Air Vehicle (UCAV) concept with smart, hingeless control surfaces on the starboard wing and conventional control surfaces on the port wing. Deflections of –10 degrees to 8 degrees for a smart trailing edge and –4.5 degrees for a smart leading edge were demonstrated. The effectiveness of the leading edge to maintain roll control as the trailing-edge "aileron" became less effective with increasing dynamic pressure was also demonstrated.

Current Year Accomplishments:



Phase 2. Test 2 Model in the Langley Transonic Dynamics Tunnel

The second Phase 2 test in the TDT (which began in April 2001) focused on control surface deflection rate. To achieve the desired higher deflection rate, Northrop Grumman replaced the Phase 2 Test 1 SMA-actuated trailing-edge control surface, which had a maximum potential actuation rate of less than 3 Hz, with an alternative smart technology concept: a control surface utilizing eccentuator arms driven by piezoelectric ultrasonic motors. The result was a fast (>70 deg/sec), morphable, hingeless control surface that maintained or improved the aerodynamic performance benefits demonstrated during the previous three tests. Uniform conventional control surface deflections of up to ±20 degrees, uniform smart control surface deflections of up to +20/-15 degrees, and 71 different smart control surface spanwise variation shapes were tested at Mach numbers up to 0.8 and dynamic pressures up to 150 psf. To the best of the test team's knowledge, the second Phase 2 test was also the first demonstration of such a control surface under realistic loads, sized such that it could be used on an operational UAV. During the test, three LaRC-developed instrumentation systems were used: two model deformation measurement systems to measure deflections of the smart trailing-edge control surface (Videogrammetric Model Deformation (VMD) and Projection Moiré Interferometry (PMI)) and a sting whip correction package to provide model angle of attack. All three systems had been utilized during previous Smart Wing entries but exercised new capabilities for the first time during this entry. An additional model deformation system (Optotrak) was also used for the second time during the program.

Lessons Learned:

1. Wing twist due to aerodynamic loading and smart control surface segment twisting during non-uniform deflections both influenced the external model deformation measurements. This is because the external measurement systems observed the wing motion from a fixed reference frame, resulting in measurements that encapsulated the total motion of the wing.
2. The VMD retro-reflective dots did not adhere well to the smart control surface silicon/RTV skin material.
3. Even after all non-essential lights were extinguished, the Optotrak system experienced interference from the tunnel lights during both Phase 2 entries.

Future Work: The Smart Wing program officially ended on September 30, 2001.

Formal and Informal Documentation Available:

1. Kudva, J. N.; et al: *Adaptive Smart Wing Design for Military Aircraft: Requirements, Concepts, and Payoffs*. SPIE North American Conference on Smart Structures and Materials, Vol. 2447, Paper No. 2447-04, 1995.
2. Kudva, Jayanth N.; Martin, Christopher A.; Scherer, Lewis B.; Jardine, A. Peter; McGowan, Anna-Maria Rivas; Lake, Renee C.; Sendeckyj, George P.; Sanders, Brian P.: *Overview of the DARPA/AFRL/NASA Smart Wing Program*. SPIE Conference on Smart Structures and Materials, Industrial and Commercial Applications of Smart Structures Technologies, Vol. 3674, Paper No. 3674-26, pp. 230-236, 1999.
3. Kudva, J. N.; Sanders, B.; Pinkerton-Florance, J.; Garcia, E.: *Overview of the DARPA/AFRL/NASA Smart Wing Phase 2 Program*. SPIE Conference on Smart Structures and Materials, Industrial and Commercial Applications of Smart Structures Technologies, Vol. 4332, Paper No. 4332-48, 2001.
4. Kudva, J. N.; Sanders, B.; Garcia, E.: *Overview of the DARPA/AFRL/NASA Smart Wing Phase 2 Program*. SPIE's 9th Annual Symposium on Smart Structures and Materials, Vol. 4698, Paper No. 4698-04, 2002. Expected publication date, fall 2002.
5. Martin, C. A.; et al: *Design, Fabrication and Testing of the Scaled Wind Tunnel Model for the Smart Wing Phase 2 Program*. SPIE's 9th Annual Symposium on Smart Structures and Materials, Vol. 4698, Paper No. 4698-05, 2002. Expected publication date, fall 2002.
6. Wang, D. P.; et al: *Development, Control, and Test Results of High Rate, Hingeless Trailing Edge Control Surface for the Smart Wing Phase 2 Wind Tunnel Model*. SPIE's 9th Annual Symposium on Smart Structures and Materials, Vol. 4698, Paper No. 4698-06, 2002. Expected publication date, fall 2002.
7. Scherer, L. B.; et al: *DARPA / AFRL Smart Wing Phase 2 Wind Tunnel Test Results*. SPIE's 9th Annual Symposium on Smart Structures and Materials, Vol. 4698, Paper No. 4698-07, 2002. Expected publication date, fall 2002.
8. *Smart Materials and Structures – Smart Wing Phase 1, Volumes I, II, III, and IV.* Contract Final Report, AFRL-ML-WP-TR-1999-4162, Contract Number F33615-95-C-3202, December 1998.
9. *Smart Materials and Structures – Smart Wing Phase 2*. Contract Final Report, Contract Number F33615-97-C-3213. Expected Publication, Fall 2002.

External Partners and Their Accomplishments: The Smart Wing program was led by the Northrop Grumman Corporation under a Defense Advanced Research Projects Agency (DARPA)-funded contract, which was monitored by the Air Force Research Laboratories (AFRL), and included partnering with NASA Langley Research Center for technical guidance, wind-tunnel testing, and CFD analysis.

SAMPSON - Smart Aircraft and Marine Projects System Demonstration

Jeffrey D. Flamm, 757-864-5955, j.d.flamm@larc.nasa.gov
Configuration Aerodynamics Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

Background Information:
The SAMPSON program mission was to use Smart Materials based Marine and Aircraft demonstrations as development tools to expand and demonstrate the ability of Smart Structures Technology to provide significant expansion of vehicle operating envelopes to enable new missions.

Objective of Current Work:
Demonstrate a full-scale fighter aircraft inlet with highly integrated smart structures capable of providing more than a 20 percent increase in mission radius relative to conventional fixed inlet design.

Benefits over Existing Systems:
A variable geometry inlet provides up to 20 percent increase in mission radius (relative to fixed inlet baseline design) or a corresponding increase in fuel efficiency. It also enables strike aircraft optimized for subsonic interdiction mission to also perform supersonic intercept mission.

Previous Work on This Work Package:
1. First wind tunnel test completed May 5, 2000. A full-scale F-15 inlet (modified flight hardware) was used as the test article.
2. Demonstrated a shape memory alloy (SMA) wire-based actuator to vary an inlet fore-cowl and ramp positions under simulated full-scale aerodynamic operating conditions (M = .3 to .70)
3. Verified the predicted angle of attack and sideslip for the inlet which resulted in minimum support system loads
4. Obtained pressure distributions on the lower inlet lip to support future work on lip-blunting concept.

Current Year Accomplishments:
1. Completed second wind tunnel entry, February 2001.
2. Demonstrated an SMA wire-based actuator to vary an inlet fore-cowl and ramp positions under simulated full-scale aerodynamic operating conditions (M = .3 to .80) for inlet capture area control.
3. Demonstrated nacelle lip rotation (± 20 deg) using integrated SMA rod actuators within compliant structure under simulated full-scale aerodynamic operating conditions (M = .3 to .80) for inlet capture area control
4. Demonstrated the use of integrated SMA rod actuators within compliant structure for adaptive wall shaping for compression ramp generation in lab (generated 2” bump).
5. Demonstrated the use of piezo actuators and superelastic SMA skin for lip radius change for bluntness control in lab (radius varied from r = 0.125” to r= 1.0”).
6. Analysis of Supersonic Covert Penetrator in Supersonic Covert Penetration Mission shows approximate 5 percent range increase with variable lip bluntness.

7. Analysis of lightweight strike fighter in deck Launched Intercept Mission shows approximate 20 percent range increase for combined variable capture area and compression ramp.

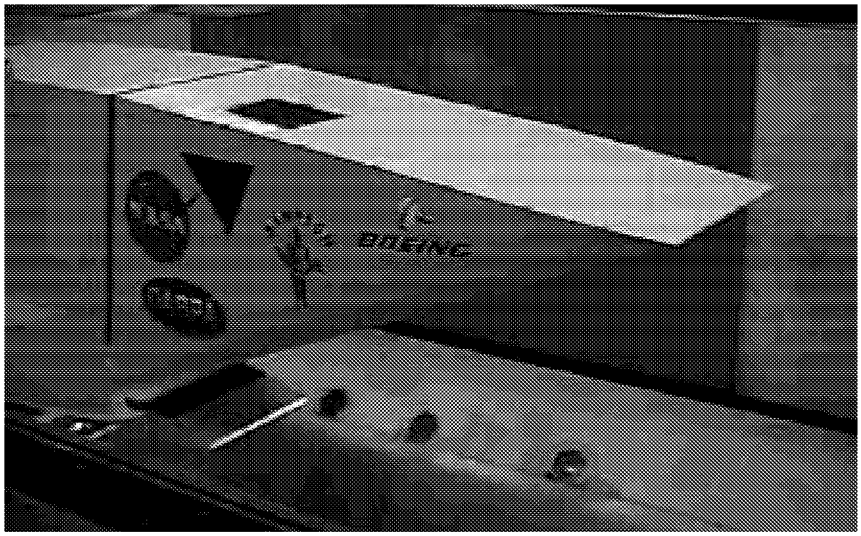
Lessons Learned:
The SAMPSON program conclusively demonstrated that smart materials can be integrated into an aircraft structure and used to provide large forces and displacements to optimize the aircraft shape at realistic (full-scale) aerodynamic conditions. An SMA actuator was successfully integrated into a full-scale F-15 inlet to replace the conventional hydraulic actuator system to rotate the inlet fore-cow and vary inlet capture area. This actuator was capable of providing up to 20,000 lbs of force and a displacement of 6 inches. The program also demonstrated that SMA rod actuators could be integrated into compliant structural configurations. The leading edge of the inlet was deflected up to 20 degrees at flow conditions up to Mach 0.8 using SMA Rods embedded in flexskin. Adaptive wall shaping using SMA Rod/flexskin technology was also successfully integrated into the F-15 inlet and demonstrated without flow. A mishap resulting in the loss of the model prevented testing the adaptive wall shaping technology under aerodynamic load. The use of piezo actuators and superelastic SMA skin was demonstrated to achieve a variable leading edge lip radius of 0.125 to 1 inch in a lab environment. Continued work is needed to develop a high-temperature SMA to open more areas on aircraft to the use of SMA.

Future Work: Program finished.

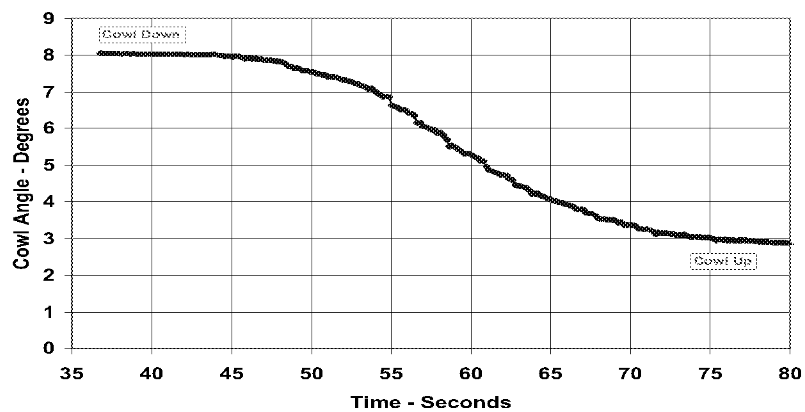
Formal and Informal Documentation Available:

1. Boeing is preparing a CD-Rom containing all program documentation.
2. Dunne, J. P., Hopkins, M. A., Erwin W. Baumann, Pitt, D. M., and White, E. V.: *Overview of the SAMPSON Smart Inlet*. 6th Annual International Symposium on Smart Structures and Materials Conference, March 1-5, 1999, Newport Beach, California.
3. Hopkins, M. A., Dunne, J. P., Baumann E. W., Pitt, D. M., and White, E. V: *Adaptive Fighter Engine Inlet*. AIAA paper 99-1512, 40th AIAA Structures, Structural Dynamics, and Materials Conference, April 12-15, 1999, St. Louis, Missouri.
4. Dunne, J. P., Pitt, D. M., White E. V. and Garcia, E.: *Ground Demonstration of the Smart Inlet*. AIAA Paper 2000-1630, 41st Structures, Structural Dynamics, and Materials Conference, April 3-6, 2000, Atlanta, Georgia.
5. Pitt, D. M.: *SAMPSON Smart Inlet First Entry – Test Report*. Boeing report, July 24, 2000.
6. Pitt, D. M., Dunne, J. P., White, E. V., Garcia, E.: *Wind Tunnel Demonstration of the SAMPSON Smart Inlet*. 8th Annual International Symposium on Smart Structures and Materials Conference, March 4-8, 2001, Newport Beach, California.
7. Pitt, D. M., Dunne, J. P., White, E. V., Garcia, E.: *SAMPSON Smart Inlet SMA Powered Adaptive Lip Design and Static Test*. AIAA-01-1359, 42nd Structures, Structural Dynamics, and Materials Conference, April 16-20, 2001, Seattle Washington.

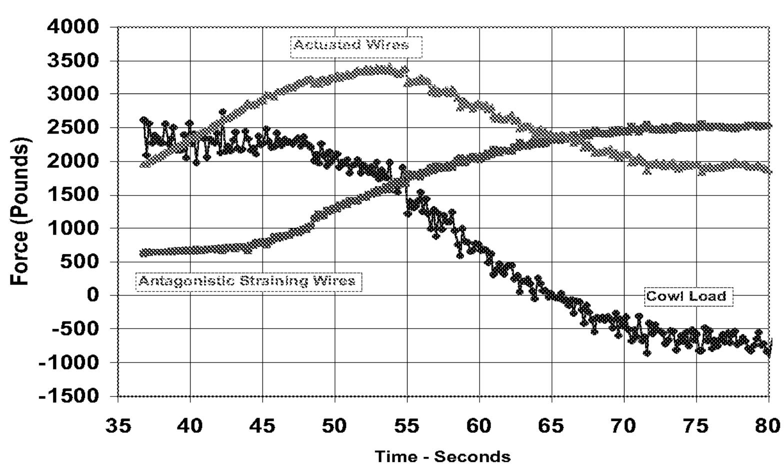
External Partners and Their Accomplishments:
The SAMPSON program was a joint program between DARPA (Sponsor), NASA (Aircraft program technical monitor, wind tunnel testing), Institute for Defense Analysis (IDA, DARPA liaison), Office of Naval Research (ONR, Marine program technical monitor), Boeing (Prime contractor), Electric Boat (marine program management), and Penn-State (core- technology, piezo actuator design/fab, aircraft lip-blunting concept design/fab).



SAMPSON F-15 Installed in NASA LaRC 16 Foot Tunnel



Cowl Up Rotation Angle vs. Time at M = 0.8



Cowl Up Rotation Loads vs. Time at M = 0.8

Langley Adaptive Aeroelastic Demonstrator

Robert Scott, 757-864-2838, r.c.scott@larc.nasa.gov
Aeroelasticity Branch, Structures and Materials Competency

Background Information:
Aeroservoelastic research using smart actuators or adaptive materials has been performed in several wind tunnel test programs. These programs include Piezoelectric Aeroelastic Response Tailoring Investigation (PARTI), Actively Controlled Response Of Buffet Affected Tails (ACROBAT), Smart Wing, Active Twist Rotor, and Active Materials Rotor programs. Additionally, there have been a variety of small wind tunnel investigations on very simple models, as well as, numerous computational studies. These research programs have provided some valuable insights into the use of smart actuators/materials for aeroservoelastic applications yet they have had some limitations. These limitations include the use of simple or unrealistic structures, retrofit applications, limited ASE tailoring performed or demonstrated, rigid models with no ASE objectives, flutter suppression marginally successful, or the program was not relevant to fixed wing configurations.

Objective of Current Work:
The objective of this work package is to explore ways to use smart structures concepts to exploit static and dynamic aeroelastic deformations to improve aircraft performance. This objective will be pursued by three main avenues of research:

1. Development of aeroelastic performance objectives and active material performance requirements.
2. Development of tools and methods for performing aeroservoelastic tailoring with active materials.
3. Evaluating technologies by performing aeroservoelastic analyses and wind tunnel testing.

Benefits over Existing Systems:
It is still unclear how or if smart structures can be used to improve the aeroelastic performance of aircraft; design and analysis tools that can be used for these structures are not mature; and hard engineering data for aeroelastic applications of these technologies is limited. This project will make contributions in all of these areas.

Current Year Accomplishments:
<u>FY 2001 Approach</u>
The work performed in FY 2001 was focused primarily on utilizing the existing Aeroservoelastic Semispan Model (ASM) as the baseline configuration for a wind tunnel testbed. New wings were to be designed to demonstrate and evaluate devices for use in controlling static and dynamic aeroelastic response to reduce loads and structural weight and increase aerodynamic performance. The first wing was to incorporate embedded Macro Fiber Composite (MFC) (piezoelectric) actuators for active aeroelastic control. In order to design this type of active structure, design tools and methods needed to be developed. Simple beam and plate finite element models (FEM) were used to develop techniques for optimizing discrete actuator locations and composite skin thicknesses and orientations. After satisfactory evaluation of these tools on simple beam/plate models, they will be applied to a simplified FEM of the ASM wing. Additionally, simple beam and plate coupons were to be fabricated and tested to verify wind tunnel model fabrication and analysis methods.

FY 2001 Accomplishments

Design/optimization tools incorporating iSIGHT and NASA Structural Analysis (NASTRAN) codes to perform simultaneous skin tailoring and actuator placement/orientation studies were implemented on beam/plate coupon finite element models. The baseline ASM wing FEM has been simplified in preparation for design/optimization studies. Several active and passive coupons have been designed and fabricated, Transonic Dynamics Tunnel (TDT) laboratories have been set up for projection moiré interferometry (PMI) testing, and PMI deflection measurements have been made for externally loaded beam/plate coupons and for MFC actuated beam/plate coupons. Ground vibration testing (GVT) and stiffness testing were performed on the baseline ASM wing. This data was compared with the wing FEM indicating generally satisfactory correlation. Several previously uncompleted components of the ASM testbed have been fabricated, and the ASM has been mothballed for future use.

Lessons Learned:

Potential fabrication methods appropriate for a wind tunnel model wing incorporating MFC actuators have been validated: MFC actuators co-cured with fiberglass prepreg skins over a honeycomb core. Mass and stiffness differences between the baseline ASM wing FEM and experimental stiffness/vibration data indicate some potential modeling and fabrication shortcomings that will need to be addressed in future wings. Finite element analysis of beam/plate coupon models that incorporate MFC actuators using nominal published properties over predicted deflections achieved experimentally. Optimization of discrete actuator locations using the simulated annealing approach available within iSIGHT was found to be computationally expensive for even small problems. In spite of these limitations, the approach did succeed in finding optimal actuator locations that were slightly better (2 percent) than the expected result.

Future Work:

1. A literature search will be performed to determine what the state of the art is and avoid duplication of effort, outside experts in the field will be consulted and possibly hired to perform evaluations and analyses, and aeroservoelastic tailoring requirements studies will be performed.
2. The in-house effort to develop an aeroservoelastic tailoring capability using the iSIGHT and NASTRAN codes will be continued. This effort will initially be exercised on simple beam/plate models with the ultimate objective being the demonstration of aeroservoelastic tailoring on a wing finite element model having MFC actuators. This effort will be supplemented with various small experimental demonstrations and correlation studies.
3. Existing wind tunnel and finite element models including the ASM will be used for evaluations. Additionally, new models will be designed and built or acquired, as necessary, to evaluate various technologies. The first wind tunnel test to be performed as part of the LAAD project will be of the Stingray Unmanned Air Vehicle (UAV). The goal of this activity will be to obtain performance data for active flow control devices.

External Partners and Their Accomplishments:

The Aerospace, Transportation, and Advanced Systems Laboratory of the Georgia Tech Research Institute is collaborating with LaRC to perform of a wind-tunnel test of the Stingray UAV to evaluate new wing skin panels with imbedded synthetic jets for virtual shape change at high angles of attack. To date, the Stingray UAV vehicle has been flight tested, and the synthetic jet wing skins are being designed.

Elastic Tailoring and Active Control of Wing Structures

David M. McGowan, 757-864-4916, d.m.mcgowan@larc.nasa.gov
Mechanics and Durability Branch, Structures and Materials Competency

Background Information:
This research can provide the understanding necessary to allow for more aggressive designs of future aerospace vehicles by coupling elastic tailoring principles with smart structures technology. An understanding of the effect of embedded actuators and sensors will also advance this technology. If successful, more aggressive designs can translate into lighter-weight, more fuel-efficient structures.

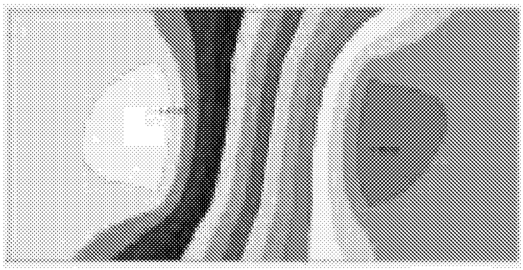
Objective of Current Work:
Develop reduced weight, adaptive/reconfigurable wing structures with enhanced structural integrity and that synergistically integrate elastic tailoring, smart component technologies, and sensing systems.

Benefits over Existing Systems:
Combines passive control (elastic tailoring) technology with active control (smart structures) technology.

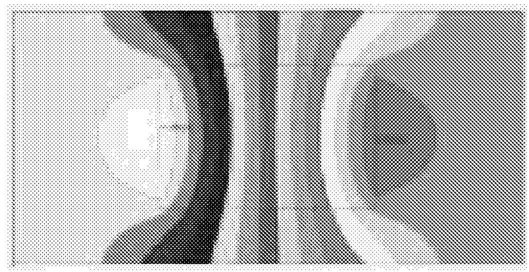
Previous Work on this Work Package: New Work Package for FY 2001.

Current Year Accomplishments:
Developed analytical models to predict the response of composite laminates with embedded piezoelectric actuators with delaminations present on one surface. Identified E-beam curing as a potential manufacturing method for producing unsymmetric laminates. Investigated the manufacturability of unsymmetric laminates that can be used in an elastic tailoring application by fabricating several unsymmetric laminates with different elastic coupling characteristics. Designed an unsymmetrically laminated composite wing box representative of the outer wing box of an F-18. Boeing, Seattle has fabricated the cover panels for this wing box. Conducted material property characterization of E-beam cured materials, and began investigating thermal post curing methods for E-beam cured laminates. Developed analysis tools for determining curing stresses for unsymmetric laminates produced by an autoclave curing process. Investigated manufacturing techniques for embedding piezoelectric actuators through the thickness of a composite laminate.

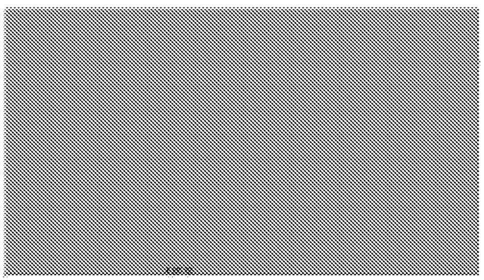
Lessons Learned:
Analytical results indicate that the presence of a delamination over one surface of a LaRC macro-fiber composite (MFC) actuator embedded into a composite laminate reduced the effectiveness of the actuator by 33 percent (based upon the maximum axial displacement occurring in the laminate). The presence of the delamination also results in unwanted out-of-plane deformation. These effects are shown in figure 1 below.



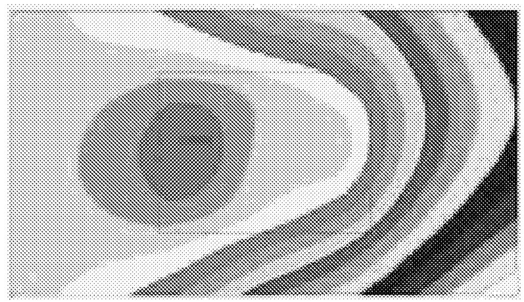
(a) No delamination, u_{max} = 1.46E-3 in.



(b) Delamination present, u_{max} = 0.976E-3 in.



(c) No delamination, w_{max} = 4.07E-10 in.



(d) Delamination present, u_{max} = 1.49E-4 in.

Figure 1. Composite laminate with embedded LaRC MFC actuator.

Fabrication demonstrations indicated that E-beam curing holds a lot of potential for manufacturing anisotropic (tailored) laminates. However, E-beam cured unsymmetric laminates have exhibited a tendency to recover some warpage primarily due to incomplete initial curing of the polymer followed by progression of the cure at room temperature.

Future Work:
Develop actuation devices and systems for configuration changes at the global and local levels. Address issues related to the integrity of composite structures with embedded morphing devices using autoclave and non-autoclave processes (e.g., SMA hybrid composites and embedded fiber-optic sensors). Develop analysis tools to investigate morphed structural response (including modeling of morphing devices such as SMA hybrid composites). Develop, implement, and validate concepts for morphing using actuation devices and systems.

External Partners and Their Accomplishments:
Virginia Tech: Residual thermal stress analysis of autoclave-cured composite laminates.
The Boeing Company, Seattle, Washington: E-beam curing of unsymmetric laminates and F-18 wing box covers.

Multifunctional Adaptive Structures

Travis L. Turner, 757-864-3598, t.l.turner@larc.nasa.gov
Structural Acoustics Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

Background Information:
Novel material systems and structures are needed for multi-mission morphing vehicles. Conventional structures are limited to single point designs and adaptability incurs large design penalties. Morphing concepts necessitate advanced materials and structures fabrication technology, characterization of the material systems and models to predict the behavior of such materials and structures.

Objective of Current Work:
Refine shape memory alloy (SMA) processing and characterization technology. Demonstrate fabrication and performance of a practical structure with embedded SMA. Validate the effective coefficient of thermal expansion (ECTE) constitutive model for SMAs and SMA hybrid composite (SMAHC) structures and facilitate implementation of the model in a commercial finite element (FE) environment.

Benefits over Existing Systems:
The LaRC SMA characterization activity is not only supplying property data for model development/validation and applications, but also uncovering unique behaviors not reported in the literature. LaRC-developed SMAHC fabrication technology is amenable to automation and is commercially viable. The LaRC-developed ECTE constitutive model for SMAs/SMAHCs is the only known model that is implicitly amenable to commercial implementation.

Previous Work on This Work Package:
A thermoelastic constitutive model (ECTE) was developed for analysis of SMAs/SMAHCs. Methods for SMA characterization and SMAHC fabrication were developed. SMAHC beam specimens were fabricated and the material system was characterized. The ECTE model was qualitatively validated against experimental results.

Current Year Accomplishments:
Further prediction-measurement correlation studies of the SMAHC beam specimens led to quantitative validation of the ECTE model and corresponding FE implementation. A contract was established with MSC.Software Corporation to implement the ECTE constitutive model within the standard solution procedures of MSC.NASTRAN, thereby becoming a fully supported material system option. A side benefit of this development is that MSC.Software is committed to implementation of temperature dependent material properties for their full element library. A panel specimen with bi-directional SMA reinforcement was fabricated and thermal-structural-acoustic test hardware was designed and fabricated, figure 1. Random vibration and acoustic transmission tests are currently under preparation. A data acquisition and control system has been developed to automate the measurement of SMA recovery force versus temperature and thermal cycle, figure 2. This capability, in combination with infrared thermography, will provide an enormous improvement in test accuracy, repeatability, and data rate. The control system is test stand independent and will also form a basis for automation of other related tasks, such as SMA actuator training. A complimentary microstructural analysis capability is under

development to help discern the relationships between thermomechanical history, crystalline structure/phase content and thermomechanical properties. A concept for automation of the prestrain operation on SMA actuators has been developed and system component selection is underway. This technology will not only vastly reduce the time/effort to process SMA actuators and fabricate SMAHC specimens, but will also provide an automated SMA actuator preprocessing capability that can be integrated into a robotic tape laying system for fully automated SMAHC fabrication.

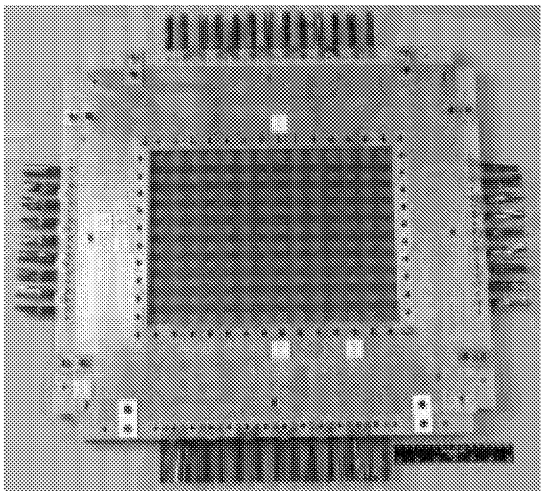


Figure 2. SMAHC panel thermal-structural-acoustic test assembly.

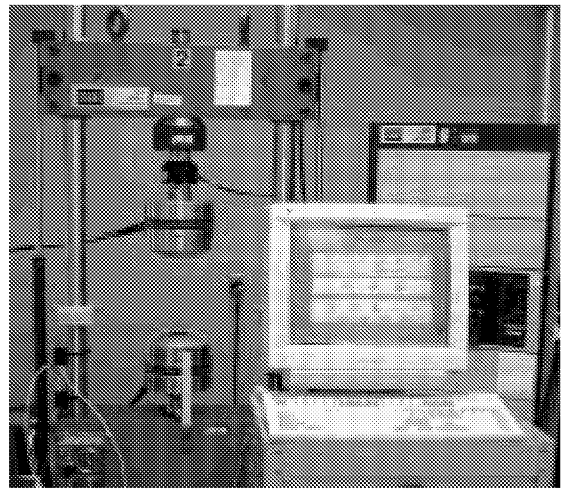


Figure 3. SMA recovery force test automation system

Lessons Learned:
ECTE model may be difficult to use for shape control prediction. SMA characterization/processing is very tedious and labor intensive, necessitating automation. SMA characteristics are very complex, which impacts implementation and modeling.

Future Work:
Develop models for shape control and implement in commercial FE environment. Expand SMA characterization for shape control modeling and applications. Fabricate benchmark shape control specimens for demonstration and model validation. Investigate active/passive flexible skin technology. Investigate embedded fiber optic strain measurement for closed-loop shape control.

Formal and Informal Documentation Available:
1. Turner, Travis L. *A New Thermoelastic Model for Analysis of Shape Memory Alloy Hybrid Composites*. Journal Intell. Mat.. Sys. & Struct. 11(5) 382-394, May 2000.
2. Turner, Travis L. *Thermomechanical Response of Shape Memory Alloy Hybrid Composites*. NASA TM-2001-210656, January 2001.
3. Turner, Travis L. *Experimental Validation of a Thermoelastic Model for SMA Hybrid Composites*. *SPIE's 8th Annual Internat'l Symposium on Smart Structures and Materials*, March 4-8, 2001, Newport Beach, California, SPIE 4326-24.
4. Turner*, Travis L.; Lach, Cynthia L.; Cano, Roberto J. *Fabrication and Characterization of SMA Hybrid Composites*. SPIE's 8th Annual Internat'l Symposium on Smart Structures and Materials, March 4-8, 2001, Newport Beach, California, SPIE 4333-60.

External Partners and Their Accomplishments:
MSC.Software activity detailed above.

Synergistic Tailored Design of Metals and Structures

Kim S. Bey, 757-864-1351, k.s.bey@larc.nasa.gov
Metals and Thermal Structures Branch, Structures and Materials Competency

Objective of Current Work:
Investigate functionally graded metallic foams as an alternative thermal protection system concept for space transportation vehicles.

Benefits over Existing Systems:
An integrated thermal-structural concept in which the load bearing structure has insulating capability and has potential for significant weight savings over current thermal protection systems (TPS). Current TPS do not have a structural function so they are parasitic from a structural viewpoint. Current TPS include coated ceramic tiles or blankets of fibrous insulation affixed to the vehicle surface and metallic panels in which fibrous insulation is encapsulated in foil and placed between an outer metal surface and the vehicle structure. A multifunctional TPS concept is based on metallic panels that are continuously graded in composition and porosity.

Current Year Accomplishments:
Heat is transferred through metallic foam by conduction through the metallic “skeleton” and by conduction and radiation through the gas in the voids. Simplified models for the effective thermal conductivity of open- and closed-cell metallic foams were developed. Results from these models indicated that sufficiently porous (~ 95 percent) closed-cell foams fabricated from hollow Titanium spheres have an insulating capability comparable to ceramic blankets and tiles.

Foams made of Titanium- and Nickel-based alloys are extremely vulnerable to oxidation and require some type of coating. Solgel processes can be used to apply a coating to protect against oxidation and to form Aerogels (extremely lightweight insulating materials) that can be used as a filler to eliminate conduction in the voids of the foam. A process was developed to prepare a foam-aerogel composite by impregnating or coating metallic foams with Silica aerogel. Microstructure characterization using SEM microscopy indicated a stable aerogel matrix with adhesion to the metal substrate. Representative micrographs of as delivered open-cell Aluminum and Nickel foam and the aerogel-impregnated foams are shown in figure 1.
(POC: Jeffrey Jordan, x45067, AMDB, AAAC)

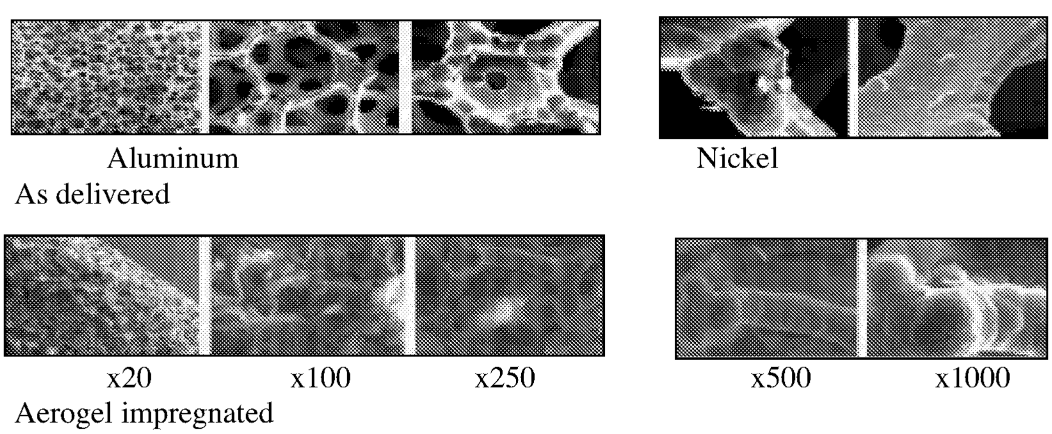


Figure 1. Micrographs of open-cell foams before and after impregnation with Aerogel.

A literature survey of Computational Materials Science and Engineering for metals was completed. A white paper presenting an overview of the theory of metallic materials at various length scales (nano to meso) and related computational techniques is 25 percent complete.

External Partners and Their Accomplishments:
Fraunhofer Inc., developed processing methods for fabricating hollow sphere foams of Titanium Aluminides. Several processes were investigated and samples were delivered with the desired 95 percent porosity. Unfortunately, the processing left the material with significant Oxygen and Carbon impurities, and the samples were extremely brittle.

A grant was initiated with the University of Florida to develop optimization methodology for functionally graded materials. Two open-cell foam panel designs were optimized by functionally grading the porosity of the foam through the panel thickness. Porosity, and likewise density, of metallic foam is controlled by varying the cell (void) size and the thickness of the metal skeleton. For one panel design, the density was graded to optimize insulating capacity (minimize the heat transfer). For the other panel design, the density was graded to minimize the mass. Results are preliminary since transients were neglected.

Lessons Learned:
Functionally graded porous materials will undoubtedly play a major role in weight-saving multifunctional concepts for space transportation. However, metallic foams lack the structural efficiency that is necessary to make them competitively viable candidates.

Future Work:
The focus of this task will shift to processing of shape memory alloys. Optimization of functionally graded materials will continue under the Integrated Thermal-Structural Concepts task of 3rd Generation Reusable Launch Vehicle (RLV) Airframe project with Space Access and Exploration Program Office (SAEPO). The computational metallic materials science component of this task will continue in the Revolutionary Metallic Materials task of Super Lightweight Multi-Functional Systems Technologies (SLMFST) project, in the Aerospace Vehicle Systems Technology Office (AVSTO).

Formal and Informal Documentation Available:

1. Fraunhofer USA – Delaware. *Fabrication of Gamma Titanium Aluminide Closed-Cell Foams*. Final Report, September 2001.
2. Venkataraman, S., Zhu, H., Sankar, B.V., and Haftka, R. T. *Optimum Design of a Functionally Graded Metallic Foam Thermal Insulation*. Proceedings of the American Society for Composites-16th Technical Conference, Blacksburg, Virginia, September 9-12, 2001.
3. Zhu, H., Sankar, B.V., Haftka, R. T., and Venkataraman, S. *Minimum Mass Design of Insulation Made of Functionally Graded Material*. Accepted for presentation at the 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Denver, Colorado, April 22-25, 2002.

Autonomous Adaptive Control Systems

Randolph Cabell, 757-864-5266, r.h.cabell@larc.nasa.gov
Structural Acoustics Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

Background Information:
Existing control approaches require precision apriori models of target systems. This approach seeks to utilize adaptive control in combination with on-line ID and fuzzy logic rules to attain and maintain high performance for a system with slowly varying dynamics.

Objective of Current Work:
Develop non-model based control approaches and control systems that incorporate Generalized Predictive Control (GPC), on-line system ID, and fuzzy logic for optimum performance in the presence of changing system dynamics. Fuzzy logic will be used to adjust controller parameters and monitor control energy in order to optimize performance with minimal controller complexity and power.

Benefits over Existing Systems:
Produce controller technology capable of regulating a variety of systems for which no offline analytical/numerical model is available, or where changing dynamics make an offline model impractical. Application will be to dynamic systems across a broad frequency range, with initial interest on reducing noise radiation from structures and tones generated by high-speed flow across cavities.

Previous Work on this Work Package:
Validation of Thermal Acoustic Fatigue Apparatus for launch blast dynamic simulation on structural panels.

Current Year Accomplishments:
A multi-rate adaptive vibration controller was demonstrated on a clamped Aluminum panel. The dynamics of the panel were varied with time by adjusting the pressure in a closed cavity on one side of the panel. The control gains were updated every few seconds to maintain stability and closed loop performance using an online system ID procedure coupled with a generalized predictive control algorithm. Peak reductions of 10dB were maintained while the natural frequencies of the panel shifted by a factor of two due to the changing pressure and the number of modes in the controller bandwidth tripled, see figure 1.

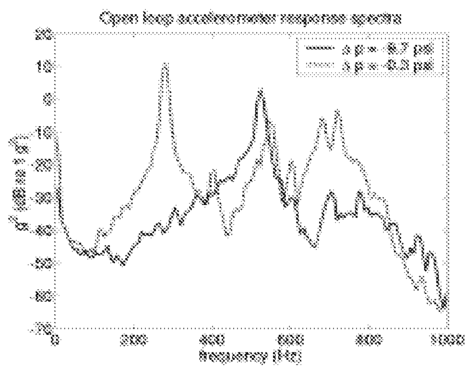


Figure 1. Bounds of panel dynamics during test (left) and controller performance (right)

Lessons Learned:
A multi-rate control approach, where the control gains are periodically updated based on new system ID data, can be used to regulate systems with changing dynamics. However, the problem is not simple due to issues such as the need to inject random noise into the system in order to obtain an accurate ID, and the rate at which the control gains are updated versus the rate at which the system dynamics are changing.

Future Work:
Apply non-model based control approach to regulation control problems, in addition to the disturbance rejection applications covered by the FY 2002 work. This means using this technology in more conventional control areas such as flight control surfaces on advanced concept vehicles. The emphasis of the work always includes real-time implementations, so as the control algorithms mature, we will start implementing the controllers in compact, power efficient packages, such as low-power, low cost digital signal processors.

Formal and Informal Documentation Available:
1. Cabell, R. H., and Gibbs, G. P. *Hybrid active/passive control of sound radiation from panels with constrained layer damping and model predictive feedback control.* Proceedings of Noise-Con 2000, December 3-5, Newport Beach, California.
2. Lin, C. and Juang, J. *Self-tuning of Design Variables for Generalized Predictive Control.* NASA TM-2000-210619.
3. Gibbs, G.P, Eure., K.W., and Lloyd, J.W. *Active Control of Turbulent Boundary Layer Induced Sound Radiation from Aircraft Style Panels.* Proceedings of Active-99, Ft. Lauderdale, Florida.
4. Juang J. and Phan M. *Deadbeat Predictive Controllers.* NASA TM-112862, May 1997.

External Partners and Their Accomplishments:
Funded Ph.D. student at Virginia Tech has developed analytical and physical model to study system dynamics to discern generalized fuzzy logic rules for continuously optimum, autonomous controller.

Feedback Control Using Piezoelectric Actuators: Do's and Don'ts

Lucas G. Horta 757-864-4352, l.g.horta@larc.nasa.gov
Mercedes C. Reaves 757-864-1306, m.c.reaves@larc.nasa.gov
Structural Dynamics Branch, Structures and Materials Competency

Background Information:
Piezoelectric actuators continue to be evaluated for in applications where solid-state actuation provides better, lighter, and more efficient means to mechanically deform a system. Often feedback control is used for vibration control using these types of actuators, thus our interest was to validate analytical models while operating the actuators in closed-loop. Two control designs were implemented using co-located and non-collocated actuator/sensor configurations. For the co-located configuration a PDVF sensor was selected whereas for the non-colocated case a displacement sensor was used.

Objective/Approach:
To experimentally validate a NASTRAN model of a closed-loop system a 16" x 2.78" aluminum beam was fitted with a piezoelectric patch and a PVDF film bonded onto the patch. With the beam clamped at one end the actuator/sensor pair, shown in photograph in figure 1, was bonded near the root of the beam and used for excitation and control. Frequency response data were used to compare results from analysis and test.

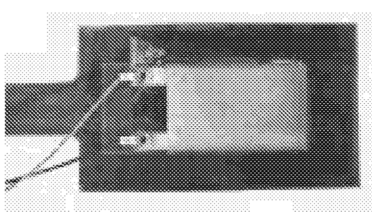


Figure 1. Photograph of piezoelectric actuator with PVDF film

Previous Work on this Work Package:
Previous work concentrated on developing modeling tools for systems with piezoelectric actuators. Included with these tools is a significant number of script files developed for interfacing finite element codes with MATLAB and also to generate state space models for control design.

Current Year Accomplishments:
Open loop test data for the aluminum beam were compared to predictions from NASTRAN. Figure 2 shows frequency response functions from PVDF output to actuator input, non-dimensional magnitude (top) and phase (bottom).
Solid line is test and dashed line is NASTRAN analysis. Several features of the plot are worth noting; first the PVDF output corresponds to strain rate in the 0

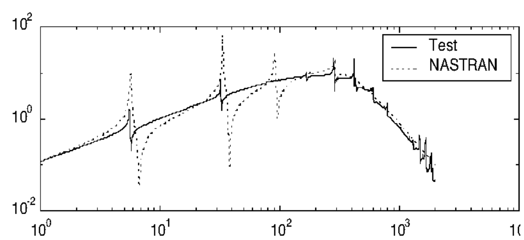


Figure 2. Test and NASTRAN frequency response functions using PVDF sensor.

to 100 Hz range, resonant frequencies appear in alternating patterns (often referred to as alternating pole-zero pattern), and analytical predictions always over-predict the magnitude changes.

Lessons Learned:
Since the PVDF output corresponds to strain rate; it seemed natural to use it in a local feedback loop. Under ideal conditions a closed-loop system using the co-located actuator/sensor pair should result in an inherently dissipative system. Although the preceding statement is true, because of the alternating pole-zero pattern, the effectiveness of such control system is limited by the proximity of the poles to the zeroes. Poles and zeroes in close proximity tend to cancel each other when the feedback loop is closed, making the control system ineffective. This was in fact what happened in our closed-loop tests. Although the occurrence of alternating pole/zero patterns has been reported in the control community when co-located sensor/actuator pairs are used, this example emphasizes the inability to design effective control systems using only local information. Magnitude overprediction in the analysis is a result of slight errors in the predicted location of the poles and the zeroes. Since our main goal was closed-loop model validation, data from a displacement sensor were used instead to close a feedback loop using the piezoelectric actuator. A frequency response function is shown in figure 3 with experimental data for the open loop, closed-loop, and closed-loop predictions. The model predictions are in agreement with test results and this closed-loop system is very effective in attenuating structural responses.

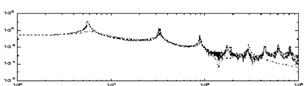


Figure 3. Test and NASTRAN frequency response functions using displacement sensor

Future Work: Since most of the necessary tools have already been demonstrated, this effort will not continue.

Formal and Informal Documentation:
Results from various approaches to model piezoelectric actuators was published in the following papers.

Reaves, M.C., and Horta, L.G.: *Test Cases for Modeling and Validation of Structures with Piezoelectric Actuators*. AIAA 2001-1466. Proceedings of the AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, Seattle, Washington, April 16-19, 2001.

Probabilistic Approach to Model Update of the Aerostructures Test Wing (ATW)

Lucas G. Horta 757-864-4352, l.g.horta@larc.nasa.gov
Mercedes C. Reaves 757-864-1306, m.c.reaves@larc.nasa.gov
Structural Dynamics Branch, Structures, and Materials Competency
David F. Voracek, 661-276-2463, *d.f.voracek@dfrc.nasa.gov*
Dryden Flight Research Center

Background and Objectives:
NASA Dryden Flight Research Center has developed a technique to predict the onset of flutter by analyzing flight data from test points at which the aircraft is stable. A flight experiment, using the Aerostructures Test Wing (ATW), was formulated to validate the technique. NASA Langley Research Center was asked to develop the structural excitation scheme and to support the modeling effort. After initial static and dynamic test data were obtained, correlation of test versus analysis showed significant discrepancies. Often finite element parameters need to be adjusted to get better agreement with experimental results. Normally, model updating is heuristic and often performed by a skilled analyst with in-depth understanding of the model assumptions. Since parameter uncertainties play a key role in understanding and improving analytical models, probabilistic analysis tools, developed for reliability and risk analysis, have great potential for guiding the update process.

Benefits over Existing Systems:
To our knowledge this is the first time probabilistic tools have been used at NASA LaRC to update finite element models. Understanding parameter uncertainty is critical to reconcile models with test results. The present study demonstrates new capabilities of analysis tools available to most users.

Previous Work:
Previous studies concentrated on enhancement and validation of commercial modeling tools to model structures with piezoelectric actuators and the implementation of optimization tools for optimal placement of piezoelectric actuators and sensors.

Accomplishments and Lessons Learned:
Prior to certifying the ATW configuration for flight, several static and dynamic tests were performed. Load certification up to 125 percent of design limit loads were conducted in both bending and torsion. Figure 1 shows a side view photograph of the bending test setup. Displacement data were measured using linear variable differential transducers (LVDT) at eight locations on the wing. In the study, Young's modulus was one of the selected parameters for the uncertainty analysis because reported values vary significantly.

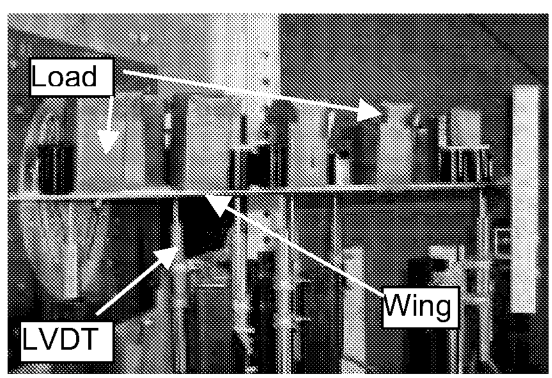
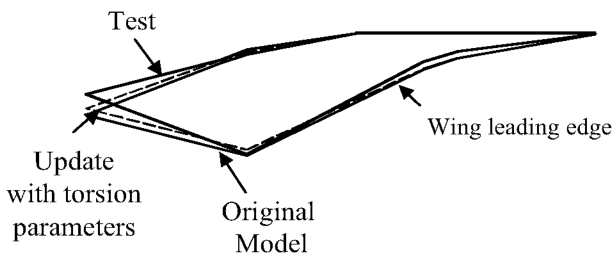


Figure 1. Photograph of ATW bending test

Other parameters selected for study affected the root bending stiffness. All parameters were assigned an upper and lower bound with uniform distribution functions to convey our lack of knowledge and confidence in the nominal values.

A commercial probabilistic analysis code named UNIPASS was used to determine the most probable point (MPP) solution for both bending and torsion. Figure 2 shows a summary of



	Torsion test	Original Model Torsion	MPP Torsion Solution Pf=0.63
Loc	Disp. (in) Mean Std. Dev.	Disp. (in)	Disp. (in)
1	0.437-(5.14e-4)	0.442	0.425
11	0.220-(1.45e-4)	0.295	0.261
56	0.102-(2.33e-4)	0.131	0.129
66	0.095-(1.95e-4)	0.107	0.098
67	0.064-(2.11e-4)	0.090	0.090
77	0.058-(2.03e-4)	0.076	0.069
100	0.002-(1.90e-4)	0.013	0.013
110	0.003-(1.99e-4)	0.007	0.006

Component	Parameters	Nominal Values	MPP Torsion Pf=0.63
Spar	E_{11} ^{2})	1.58×10^7	1.77×10^7
	E_{11s} ^{2})	2.67×10^6	2.64×10^6
	E_{22s} ^{2})	2.67×10^6	2.64×10^6
	E_c ^{2})	13.1×10^3	9.97×10^3
	k_b	2.2×10^4	2.54×10^4

Figure 2. Model update results for ATW torsion case

results using data from the torsion tests only. The upper left plot shows a comparison of the wing displacements before and after the parameter updating as indicated in the bottom table.

Also shown in the upper right table are the predicted and measured displacements. Comparison of numerical values from tests and the updated solution showed significant improvement over results using the nominal values. Nevertheless, individual errors remained as high as 40 percent. For the torsion solution, parameter changes up to 24 percent are required to reconcile test with analysis. Also shown in the table is the probability of the solution being the true solution as Pf=0.63. Solutions for this class of problems are heavily dependant upon the initial distribution functions. Subsequent work to improve results needs to use a Bayesian approach to allow for the initial parameter distribution functions to be updated based on experimental data.

Future Work: Complete the model update for the dynamic case and document results.

Formal and Informal Documentation:
Horta, L. G., Reaves, M. C., and Voracek, D. F. *A Probabilistic Approach to Model Update*. Proceedings of the First Annual Probabilistic Methods Conference, June 18-19, 2001, Newport Beach, California. Also NASA TM-2001-18097.

External Partners and Their Accomplishments:
David F. Voracek from NASA Dryden Flight Research Center, ATW flight experiments project lead.

Aerostructures Test Wing (ATW) Excitation System Design and Performance Test

Mercedes C. Reaves 757-864-1306, m.c.reaves@larc.nasa.gov
Lucas G. Horta 757-864-4352, l.g.horta@larc.nasa.gov
Structural Dynamics Branch, Structures and Materials Competency
David F. Voracek, 661-276-2463, d.f.voracek@dfrc.nasa.gov
Dryden Flight Research Center

Background and Objectives:
A problem in validating flight flutter prediction techniques is that flight flutter data near the onset of instability is extremely challenging to obtain due to flight safety concerns. NASA Dryden Flight Research Center developed a flight flutter prediction technique that predicts the onset of instabilities by analyzing flight data from test points at which the aircraft is stable. A flight experiment, called the Aerostructures Test Wing (ATW), was formulated to validate the technique. Adequate structural excitation was an important requirement to the success of the flutter test. The Structural Dynamics Branch at NASA Langley Research Center (LaRC) was assigned the task of providing an optimal piezoelectric actuator configuration to initiate and/or control flutter modes of the aerostructures test wing.

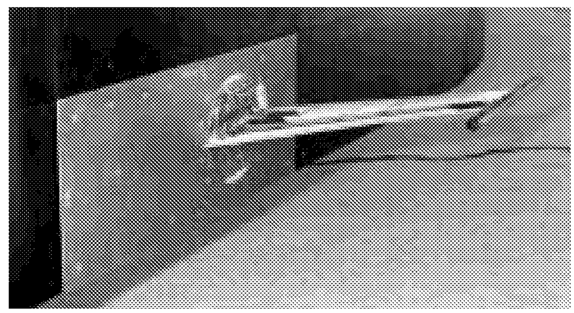


Figure 1. Aerostructure Test Wing (ATW) with piezoelectric actuators

Benefits over Existing Systems:
NASA LaRC experience in the use of piezoelectric actuators for structural vibration control as well as the intrinsic characteristics of piezoelectric actuators: lightweight, low power requirements, broadband excitation capability and easy of use, met all the application requirements.

Previous Work:
Previous studies concentrated on enhancement and validation of commercial modeling tools to model structures with piezoelectric actuators and the implementation of optimization tools for optimal placement of piezoelectric actuators and sensors.

Accomplishments and Lessons Learned:
Optimal placement of actuators using a baseline ATW finite element model was completed. Size of actuators was selected based on mass and stiffness constraints. A

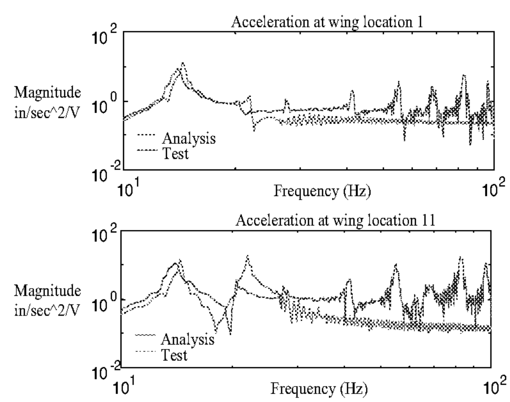


Figure 2. Test vs. analysis frequency response function at wing tip locations

total of six 3” x 1.75” actuators were placed on the structure, 3 on the top surface and 3 on the bottom surface of the wing skin. Figure 1 shows a picture of the ATW with the surface mounted piezoelectric actuators. Analytical simulations and ground vibration tests verified that response levels from the wing structure were significantly above the noise floor for accelerometer sensors. Figure 2 shows the correlation of test and analysis. The first frequency resonance was predicted within 2 percent and the second resonance within 11 percent. Results of the piezoelectric actuation system performance during the flight, comparing the response from the excitation system to natural atmospheric turbulence are shown in figure 3. The atmospheric turbulence did not excite the torsion mode of the wing at this flight condition. The piezoelectric excitation clearly made this mode observable during the flight. The piezoelectric excitation also provided a higher response in the bending mode of the ATW. These results clearly demonstrate our ability to model and analyze ‘smart structures’ at the early stages of the design process. Therefore reducing cost and the design-analysis-test cycle of flight test articles such as the ATW.

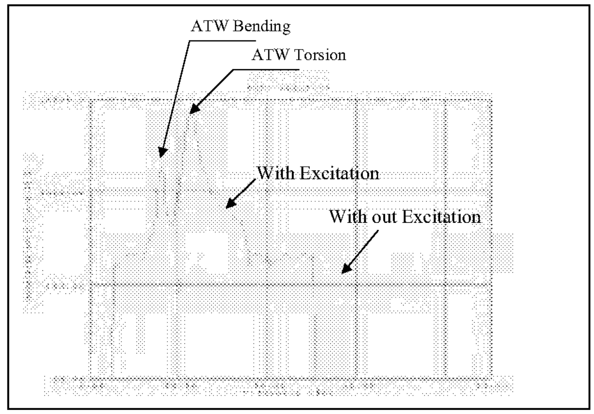


Figure 3. Accelerometer response with and without piezoelectric excitation

Future Work: Task has been completed.

Formal and Informal Documentation:
Voracek, D., Reaves, M. C., Horta, L. G., Potter, S. *Ground and Flight Test Structural Excitation using Piezoelectric Actuators*. Submitted to AIAA 2002, AIAA/ASME/ASCE/AHS/ASC Structural Dynamics and Materials Conference.

External Partners and Their Accomplishments:
David Voracek from NASA Dryden Flight Research Center, ATW flight experiments project lead.

Development of a Self-Sensing Piezoelectric Actuator

Lucas G. Horta 757-864-4352, l.g.horta@larc.nasa.gov
Mercedes C. Reaves 757-864-1306, m.c.reaves@larc.nasa.gov
Garnett C. Horner, 757-864-1684, g.c.horner@larc.nasa.gov
Structural Dynamics Branch, Structures and Materials Competency

Background Information:
Piezo-electric actuators have been used and studied for many engineering applications because they provide for lightweight yet powerful actuation systems. Often integration of the actuator onto the host structure is easy, but the means to measure the induced actuation levels locally are not. Several studies have been performed using the same piezoceramic elements for both sensing and actuation, often referred to as a sensor actuator. Although this is an effective way to sense the motion of the host structure, the voltage levels of the drive and sensor signals are orders of magnitude apart. In addition, the electronics required to recover the sensor signal is far more complex. Typical self-sensing electronic circuits are designed as a multi-layer circuit to isolate the drive signal from the sensor signal.

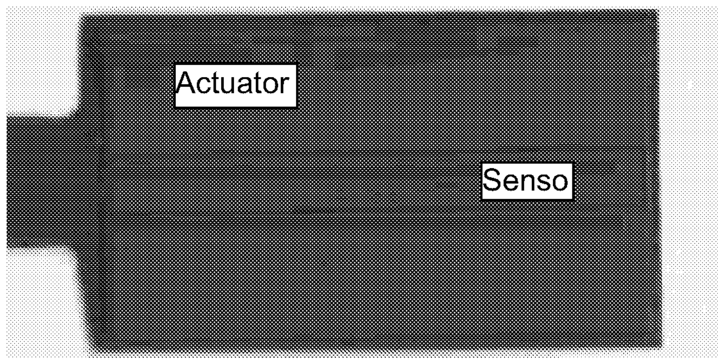


Figure 1. Self-sensing actuator

Objective:
The main objective of this work was to experimentally demonstrate a self-sensing piezoelectric actuator.

Accomplishments and Lessons Learned:
A new self-sensing design was developed and tested where part of the actuator material was carved out (isolated) for sensing. A prototype is shown in the figure 1 photo. Of course, carving out a portion of the material for sensing the amount of material available for actuation, but this is a small price to pay when compared to the simplicity of this arrangement, which requires no additional electronics.

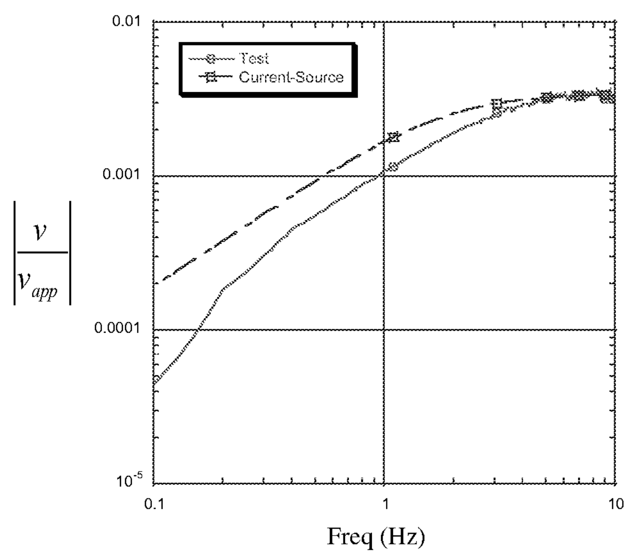


Figure 2. Frequency response of self-sensing actuator

Straining of the sensor part is proportional to thecharge generated in the material. For the study undertaken, the main goal was to show the ability to sense the induced charge/strain while actuating the material. To accomplish this, the self-sensing actuator was bonded onto a clamped aluminum beam. This allows transferring of strain from the actuator region to the sensor region. To properly validate results from the sensor, one would need to calibrate the sensor using the geometry and some known input strain. This was beyond the initial goal. To examine the sensor output, the sensor circuit can be modeled in various ways. Since charge is being generated, a current source analogy comes to mind. The equation representing the circuit is given by $\frac{v}{v_{app}} = \gamma\left(\frac{Rs}{1+RCs}\right)$, where v is the induced voltage, v_{app} is the applied actuator voltage, R is the load/leakage resistor, C is the capacitance, s is the Laplace's transform, and γ is a calibration capacitance. For the actuator/sensor combination shown in figure 1, the measured capacitance was C= 16.4 nF. Curve-fitting the test data using this circuit equation resulted in R= 5.38×10^{6} ohms and a gain value of $\gamma = 5.614\times10^{-13}\,F$. A comparison of the test data with the curve-fitted model is shown in figure 2. Although the fitted values are in error for the low frequency region, the break frequency is predicted well. With this combination of resistor and capacitor the break frequency for the electronics circuit is $1/RC = 1.8\,Hz$. Below this frequency, the sensor output is proportional to the strain rate but above it is proportional to strain. In the transition region near the break frequency the sensor output cannot be used as either strain or strain rate. To use the output voltage of the sensor as a signal proportional to strain, a factor of 10 or higher frequency separation should be observed between the frequency region of interest and the circuit frequency.

Future Work:
This simple study demonstrated the ability to sense and command signals in very close proximity without corrupting the sensor data. Many variations of the configuration are possible to minimize the sensor area while maximizing the actuator output. Ingenious ways to calibrate the sensor are also needed to validate analytical models of the self-sensing actuator, however, no further work in this area is anticipated due to funding constraints.

Biologically-Inspired Flight Systems FY 2001 Research Summaries

Biologically-Inspired Flight Concepts

Barry S. Lazos, 757-86-45731, b.s.lazos@larc.nasa.gov
Flow Physics and Control Branch, Aerodynamics, Aerothermodynamics and Acoustics Competency

Background Information:
Commercial aircraft configurations have not significantly changed for decades. This is because few advancements have been made in the areas of drag reduction, flow control and noise abatement to prompt such changes. Certain morphological features found on avian and marine creatures are expected to limit energy consumption, increase maneuverability, and reduce noise levels. Application of similar features to a mechanical flight system may provide improvements in these same areas.

Objective of Current Work:
The objective of this work is to identify morphologies in nature that have the potential for active or passive drag and/or noise reduction as well as flow control for application to subsonic transport aircraft, small scale Unmanned Aerial Vehicles (UAV), and marine vehicles.

Benefits over Existing Systems:
This work has the potential to improve drag, noise and control characteristics of manned and unmanned aerial and marine vehicles using highly evolved methods found in nature. The benefits include energy savings, lower noise and pollution levels, and improved safety and maintainability features.

Previous Work on This Work Package:
Work began in this area in 2000 with a comprehensive literature review of existing knowledge in control techniques found in biological systems. (See below for reference.)

Current Year Accomplishments:
1. Extensive literature review of the state-of-knowledge in induced drag and control techniques. Results revealed induced drag can account for between one-third and one-half of the drag of a commercial aircraft in cruise. Induced drag reduction methods may additionally diminish wake vortex intensity and noise levels.
2. Identification of several promising morphologies and selection of three biologically-inspired wing configurations. One wing was modeled directly after the wing of a seagull in gliding flight (Gull Wing), another was inspired by the fin morphology of sharks (Shark Wing), and the last was inspired by the wing shape of some shore birds and supported by theory (HECS Wing).
3. Tests of these three wing configurations were conducted in the BART facility. Data acquired included forces and moments, model deflection, and wing surface pressure and shear-stress topologies. Loads data show that the HECS (Hyper-Elliptic Cambered Span) wing provides a 14 percent average improvement in lift-to-drag over the planar-elliptic wing used as a baseline (see figure 1).

Lessons Learned:
In order for progress to be made in the adaptation of biologic configurations to mechanical flying systems, a collaborative effort must be developed between engineers and biologists.

1. Aeroelastic and control features of animal morphologies are thought to be a key issue. Duplicating this behavior will require detailed knowledge of the internal structure.
2. An understanding of animal morphological changes that result in specific maneuvers and the associated flow physics is important for the development of improved mechanical systems.

Future Work:
Future work will include identification of the flow physics associated with the improvements obtained and testing new configurations as well as modifications of the above.

Formal and Informal Documentation Available:
Anders, John B. Anders. *Biomimetic Flow Control*. AIAA Paper 2000-2543. Presented at the AIAA Fluids 2000 Conference, Denver, Colorado, June 19-22, 2000.

External Partners and Their Accomplishments:
The Virginia Institute of Marine Sciences (VIMS) – Provided marine specimens and identification of morphologies of potential interest.

North Carolina State University – Develop GPS guidance capability on two existing vehicles, develop a low static margin flight technique, develop a UAV test vehicle for biologically-inspired wing configurations.

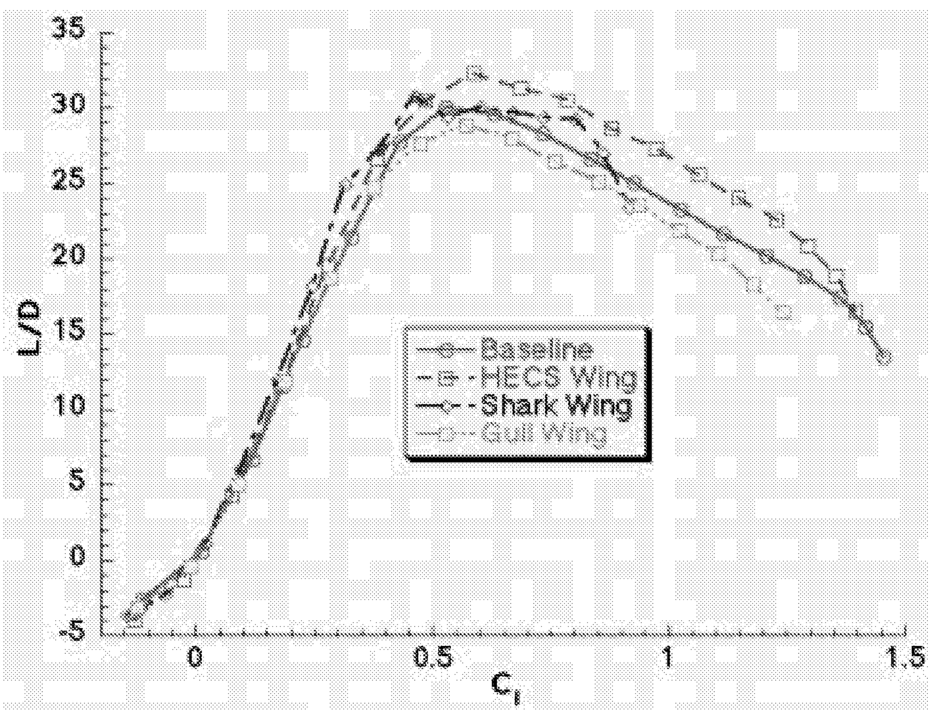


Figure 1 - Lift-to-Drag Variation with Lift Coefficient

Autonomous/Collaborative Control of Aeroelastic Fixed Wing Micro Aerial Vehicles: Characteristics of Fixed Wing Micro-UAVs

Martin R. Waszak, 757-864-4015, m.r.waszak@larc.nasa.gov
Dynamics and Control Branch, Airborne Systems Competency

Micro aerial vehicles have been the subject of considerable interest and development over the last several years. The majority of current vehicle concepts rely on rigid fixed wings or rotors. An alternate design based on an aeroelastic membrane wing concept has also been developed that has exhibited desired characteristics in flight test demonstrations and competition. The aeroelastic fixed wing micro aerial vehicle concept has been the subject of research to determine the degree to which the innovative membrane wing influences vehicle stability and control. The vehicle will subsequently be the basis for development of autonomous and collaborative control system design and implementation.

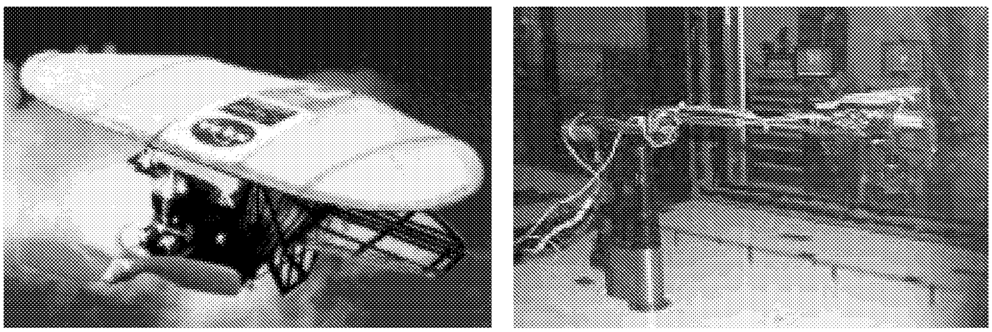


Figure 1. Micro aerial vehicle and wind tunnel arrangement

Wind tunnel testing was performed in NASA Langley's Basic Aerodynamcis Research Tunnel (BART) to identify the aerodynamic properties of the vehicle, and in particular the effects of the membrane wing. The results indicate that the elastic membrane wing allows the vehicle to achieve higher angles of attack without stalling (see figure 2).

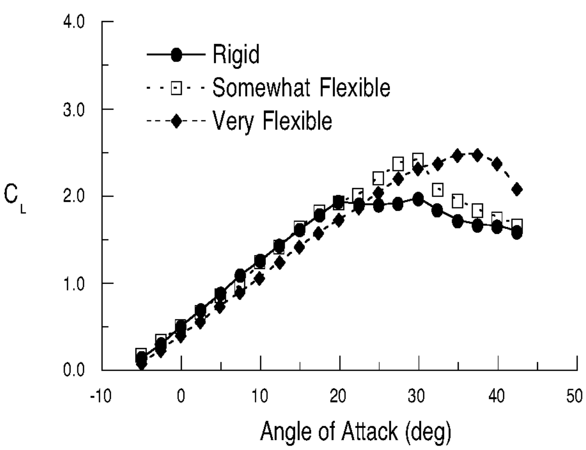


Figure 2. Lift curves for wings of various levels of flexibility

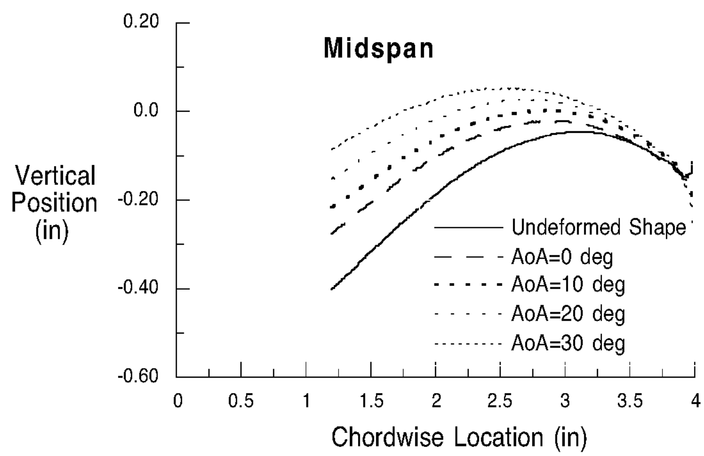


Figure 3. Deformed shapes of midspan wing section for various angles of attack

This fact coincides with significant static deformation of the wing under load, particularly at higher angles of attack (AoA), and is accompanied by extensive high frequency membrane vibration. The static deformation allows the wing to achieve a smaller effective angle of attack at high vehicle attitudes (see figure 3). Flow visualization suggests that the wing deformation contributes to weaker wing tip vortices. It is likely that there is some link between the vortex strength and structure, membrane billowing, and the stall resistance of the elastic membrane wings. The consequences of these various effects require additional study.

The vehicle was shown to be statically stable in all axes and that the nondimensional static stability derivatives of the vehicle were found to be generally larger than for typical piloted aircraft. Because the vehicle has been "tuned" using flight test experiments it is likely that the relatively large pitch and yaw stability and large dihedral effect enhance the vehicle's flying qualities. The vehicle trims near the maximum L/D, but the maximum L/D is significantly lower than other comparable micro aerial vehicles. It was also shown that streamlining of the fuselage resulted in significant improvement in the lift to drag ratio. Subsequent design changes have made better use of streamlining to improve vehicle performance.

Additional wind tunnel tests and analytical studies of the aeroelastic fixed wing micro aerial vehicle are planned or underway. In particular, a six degree-of-freedom quasi-static dynamic simulation model of the vehicle is being developed. Additional studies will emphasize efforts to develop additional understanding of the physical properties of the membrane wing concept and use this understanding to improve the design of the vehicle and pursue other aerospace applications.

The vehicle concept was developed at the University of Florida by a team led by Dr. Peter Ifju. A cooperative agreement (NCC-1-397) has been established to coordinate development of the vehicle concept and research being conducted at NASA. The University of Florida team has developed a horizon detection system that uses the onboard video camera image to detect the local horizon line. The horizon line is used to determine the pitch and roll attitude of the vehicle and that information is used to control the vehicle attitude and thereby significantly enhance the controllability of the vehicle. They have also continued to refine the vehicle design using the wind tunnel test results described above.

References:

1. Waszak, M. R.; Jenkins, L. N.; and Ifju, P. *Stability and Control Properties of an Aeroelastic Fixed Wing Micro Aerial Vehicle*. AIAA Paper No. 2001-4005. Presented at the AIAA Atmospheric Flight Mechanics Conference, Montreal, Quebec, Canada, August 6–9, 2001.
2. Fleming, G. A.; Bartram, S. M.; Waszak, M. R.; and Jenkins, L. N. *Projection Moiré Interferometry Measurements of Micro Air Vehicle Wings*. SPIE Paper No. 4448-16. Presented at the SPIE conference on Optical Diagnostics for Fluids, Solids, and Combustion, part of the SPIE International Symposium on Optical Science and Technology, San Diego, California, July 29-August 3, 2001.

3. Ettinger, S. M.; Nechyba, M. C.; Ifju, P. G.; and Waszak, M. R. *Towards Flight Autonomy: Vision-Based Horizon Detection for Micro Air Vehicles*. To appear in proceedings of AIAA Aerospace Sciences Meeting, Reno, Nevada, January 2002.
4. Ettinger, S. M.; Nechyba, M. C.; Ifju, P. G.; and Waszak, M. R. *Vision-Guided Flight Stability and Autonomy for Micro Air Vehicles*. To appear in proceedings of AIAA Aerospace Sciences Meeting, Reno, Nevada, January 2002.
5. Ifju, P. G.; Jenkins, D. A.; Ettinger, S. J.; Lian, Y.; Shyy, W.; and Waszak, M. R.: *Flexible-Wing-Based Micro Air Vehicles*. AIAA Paper No. 2002-0705. To appear in proceedings of AIAA Aerospace Sciences Meeting, Reno, Nevada, January 2002.

Component Technologies

Robert Fox, 757-864-5468, r.l.fox@larc.nasa.gov
Qamar Shams, 757-864-8156, q.a.shams@larc.nasa.gov
Microelectronics and Technical Support, Systems Engineering Competency

Background Information:
Biologically-inspired devices, particularly flight vehicles, are usually small-scale, lightweight, and operate autonomously. A common requirement for these systems is integrated and lightweight electronics and efficient sources of power. In addressing these requirements, a number of promising technologies were investigated in the area of avionics, wireless communications, and fuel cells.

Objective of Current Work:
A miniature, lightweight, efficient and inexpensive navigation system is a requirement for stability and guidance of a highly functional autonomous vehicle. The navigation system being developed at LaRC will be small enough to fit into a micro vehicle. It will have air/ground speed control, altitude control, turn coordination, GPS, telemetry, autonomous take off, flight and landing. The critical parts of a navigation system are: GPS, data logger, electronics for altitude control, telemetry and a programmable microprocessor. Technologies needed to support the navigation system development are: flexible multi-layer circuits, flip chip technology, wire bonding, surface mount, integrated passives and actives.

This work also pursued the development of an inflation and deflation mechanism capable of *morphing* the shape of a simple or complex (e.g., bio-inspired) structure. The mechanism, based on out-gassing from a reversible electrochemical cell, will be small, lightweight, reversible, and contain no moving parts. The ability to morph shapes using such a mechanism allows for the development of vehicles for use in terrestrial and space-based exploration and reconnaissance challenges that are not achievable by mechanical pump based systems.

Benefits over Existing Systems:
Existing systems are large and consume too much power to be integrated into an autonomous vehicle. The primary benefits of this work are in reduction of weight and size, increased energy density of power supplies, and in the multi-function benefits possible with an integrated design.

Previous Work on this Work Package: This work package was a new start in FY 2001.

Current Year Accomplishments:
Two high voltage power supplies were designed, proto-typed and tested during the year 2001. The high voltage power supplies are capable of producing 325 volts at five milli amperes and 650 volts at five milli amperes. The 325 volt supply is approximately one square inch and the 650 volt supply is about two square inches in area at a height of about three quarters of an inch. The circuits use standard electronic components. Recently purchased DC-DC converters will increase the current level of the high voltage amplifiers to eight milli amperes, while maintaining the same size and volume. Alternate commercially available DC-DC converters will increase the high voltage circuit from eight to sixty milli amperes. Sixty milli amperes is the current limit of

the amplifier being used. Higher current DC-DC converters will certainly increase the package size by orders of magnitude. Current levels into the hundreds of milli amperes are possible with alternate commercially available amplifiers. Higher current amplifiers generate a tremendous amount of internal heat. Dissipating this heat is a engineering nightmare. Continued work in this area (ASICs and electronic die-APL or hybrid circuits) will reduce the area of the high voltage power supplies by more than fifty percent. The development the power supplies received funding from a number of sources in the year 2001.

Wireless communications systems were developed in the year 2001 for shape control (morphing using a direct current bias), applications requiring repetition (i.e., flapping-variable voltage and frequency) and relaying information from a sensor to a remote location or requiring data logger. The ideal wireless system will have adequate battery life, transmit over a reasonable distance, avoid EMI, provide plug and play compatibility with many products from many companies, be infinitely small, self powering, self configuring, self calibrating, self locating and provide a secure RF signal for communication. The commercial wireless systems developed at LaRC use science band frequencies of 418MHz, 433MHz and 900MHZ. The wireless systems consume 300 milli watts of power, require no FCC license to operate and have a range of nearly 1000 feet in all directions. An analog signal imposed on a carrier frequency is used to produce a DC bias for shape control. Changing the DC bias level will alter the strain produced by the actuator. If a repetitive motion is required (flapping), a sine wave is imposed on the transmitter's carrier frequency. The sine wave is generated by a single electronic chip with variable amplitude and frequency. The wireless systems for shape control and repetitive motion will have the same voltage and current potential as that of the previously mentioned amplifiers. Sensors have been interfaced into the LaRC wireless system to relay critical flight data back from a biomimetic vehicle. Funding for this work during the year 2001 came from a number of places.

Future Work:
Funding sources for next year have not been secured, however, the initial work has yielded several paths for continuation and additional design objectives remain.

External Partners and Their Accomplishments:
This work involved contracts with Composite Optics, Applied Physics Labs and University of Arkansas.

Airmass Guidance

David E. Cox, 757-864-6658, d.e.cox@larc.nasa.gov
Guidance and Control Branch, Airborne Systems Competency

Background Information:
Small and mid-scale Unmanned Air Vehicle (UAV) systems have many potential applications in both military and civilian sectors. For example, they can provide visual reconnaissance of an area, be deployed in search and rescue operations, fly circuits to detect forest fires, provide mobile and secure communications relays, or gather detailed in-situ measurements for weather prediction. A common requirement for all of these missions is the endurance of the system - how long can it loiter in, or fly a circuit around, a prescribed area.

Improving lift-to-drag ratios, increasing the efficiency of propulsion systems, and increasing the energy density of fuels are direct (and important) approaches to the problem of endurance. This work, however, seeks a different and biologically-inspired approach - that of extracting energy from an unstable atmosphere during flight. The wandering albatross is able to soar for hours without flapping its wings as it makes use of vertical wind gradients in a technique known as dynamic soaring. Other birds circle in thermals to gain altitude and extend hunting range without expending additional energy.

For low-speed and lightweight UAVs the effects of atmospheric winds are not negligible, and can be a significant source of energy. The technical questions that this work package seeks to understand are: what instrumentation is required, how is a guidance law determined, and how is the necessarily autonomous guidance path integrated with the prescribed-waypoint paths found in many applications.

Objective of Current Work:
The current works seeks to develop guidance algorithms that enable an instrumented UAV to adjust its trajectory between waypoints, or choose a loitering path such that it takes advantage of favorable winds and updrafts and mitigates the effect headwinds and of sinking air.

Benefits over Existing Systems:
Existing systems fly prescribed trajectories that are independent of atmospheric effects. By considering these effects it is expected that, particularly for small and low speed UAVs, endurance can be significantly enhanced.

Previous Work on this Work Package: This work package was a new start in FY 2001.

Current Year Accomplishments:
During FY 2001, an atmospheric modeling package was obtained and ported from a Cray to a Linux computer system. The package is called TASS (Terminal Area Simulation System), and has been used to model relatively small-scale atmospheric features. The software is essentially a CFD code and produces atmospheres with vertical and horizontal winds and physically consistent variables, such as pressure, temperature, water vapor, etc. Several representative

atmospheres have been produced and will be used to pose optimization problems for a flight vehicle.

Also during FY 2001, a suitable aircraft model was developed that includes the ability to impose spatially variable winds that are a relatively large fraction of the flight speed. This model can be flown through the simulated atmosphere to determine the significance of ambient winds on flight path.

Lessons Learned:
A physically realistic atmosphere model was deemed important because it allows a feedback implementation of the optimal trajectories to be based on measurements such as pressure and temperature as well as loads from vertical wind. Potentially, this allows the algorithm to include logic for finding thermals, rather than just reacting to them. The optimization requirements, however, are for many randomly initiated atmospheres at very high grid density and this is not numerically feasible. Current plans are to use a few high fidelity simulations to determine parameters a for stochastic atmosphere model. These stochastic models with be suitable for determining optimal trajectories, provided only the loads from winds are used for feedback, not correlations between temperature, pressure, water vapor, or other physical variables.

Future Work:
The work in FY 2002 will concentrate on obtaining optimal trajectories for the existing aircraft models and simulated atmospheres. These trajectories will allow evaluation of the benefits of airmass guidance. From these optimal trajectories a guidance strategy will be determined that approximates the optimal, but operates based on feedback from measured variables.

Formal and Informal Documentation Available:
Although the area is relatively new, there has been some work on optimal soaring published in the literature, predominately in the Journal of Technical Soaring. Relevant references include:

1. Sachs, G, Knoll, A., and Lesch, K. *Optimal Utilization of Wind Energy for Dynamic Soaring*. Journal of Technical Soaring, Vol. 15, No. 2, pp. 48-55, 1991.
2. Stojkovic, B. *Generalized Speed-to-fly Theory*. Journal of Technical Soaring, Vol. 17, No. 3, pp 77-83, 1993.

External Partners and Their Accomplishments:
This work is being done in conjunction with an ICASE researcher and contract support from Research Technology Institute on the TASS software. Their accomplishments are reflected in the work described above.

Dynamics and Control of Resonant Flapping Micro-Aerial Vehicles

Dave Raney, 757-864-4033, d.l.raney@larc.nasa.gov
Dynamics and Control Branch, Airborne Systems Competency

Background Information:
With uncountable civil and military applications, micro-aerial vehicles (MAVs) represent an emerging sector of the aerospace market and may one day become as ubiquitous as cell phones. Although a number of highly capable MAV designs have been generated by several government-funded and commercial endeavors, these designs rely on relatively conventional scaled-down control approaches, and they do not possess the flight agility and versatility that would enable missions such as rapid flight beneath a forest canopy or within the confines of a building. In order to satisfy such mission requirements, it is likely that MAV designs of the future will exploit flapping flight for extreme agility. Many flying insects generate lift through resonant excitation of an aeroelastically tailored structure: muscle tissue is used to excite a structure which exhibits a particular mode shape that has been tuned to generate propulsive lift. A number of MAV concepts have been proposed that would operate in a similar fashion.[1,2] A resonance-based flapping MAV design would challenge the current state-of-the-art in flight control for vehicles with highly transient flight-dynamic characteristics.

Objective of Current Work:
This work package does not seek to develop a flapping MAV design. The goal is to develop *dynamic models* and *feedback control concepts* for vehicle designs in which resonant excitation of an aeroelastically tailored wing structure is used to generate propulsive lift for an extremely agile MAV.

Benefits over Existing Systems:
An extremely agile resonant flapping MAV would exploit unsteady aerodynamic factors such as dynamic stall to transition rapidly between flight modes, and might vary its inertial properties by stowing its wings during high-rate maneuvers. Aerodynamic characteristics, inertial properties, and flight conditions will rapidly vary over an unprecedented range. Developing methods required to control a highly agile flapping MAV will bolster our understanding of unsteady and nonlinear dynamic phenomena in general, and could also have cross-over application to technologies such as distributed flow control effectors for full-scale aircraft.

Previous Work:
Previous work focused on modification of a structural concept from a flexible fixed-wing MAV design from the University of Florida. The latex and graphite-epoxy pre-preg structure was modified to create wing planforms that were tailored to generate bird-like flapping kinematics when excited at their lowest frequency bending mode. Piezoceramic *Thunde*r wafer actuators were used to excite the structures at their resonant frequency of approximately 25 Hz (figure 1). Flow visualization revealed the presence of unsteady fluid dynamic structures acting on the flapping wings much like those observed by entomologists at UC Berkeley.[3]

Current Work/ Lessons Learned:
Current research has focused on the evaluation of thin film pvdf strain rate sensors for closed-loop control of the resonating wing structure. A controller has been developed that uses this sensor feedback to drive the wing at its fundamental resonant frequency (figure 2). Tests under time-varying reduced pressures have confirmed the system's ability to track the resonant frequency as it varies with aerodynamic damping.

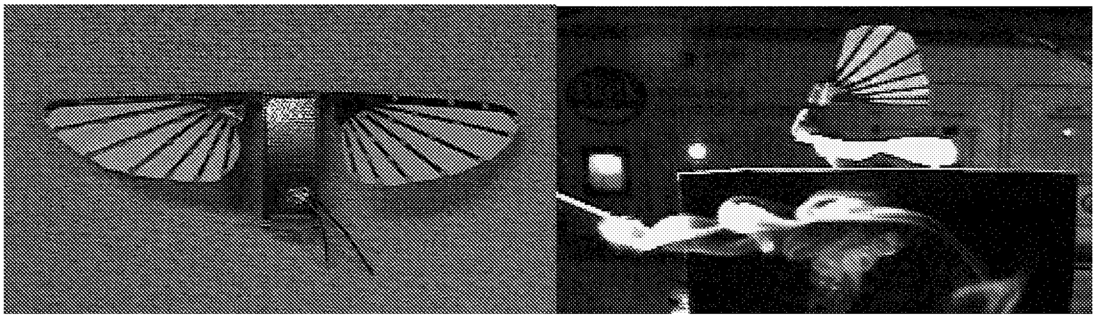


Figure 1. Resonant flapping wing structures and unsteady flow visualization.

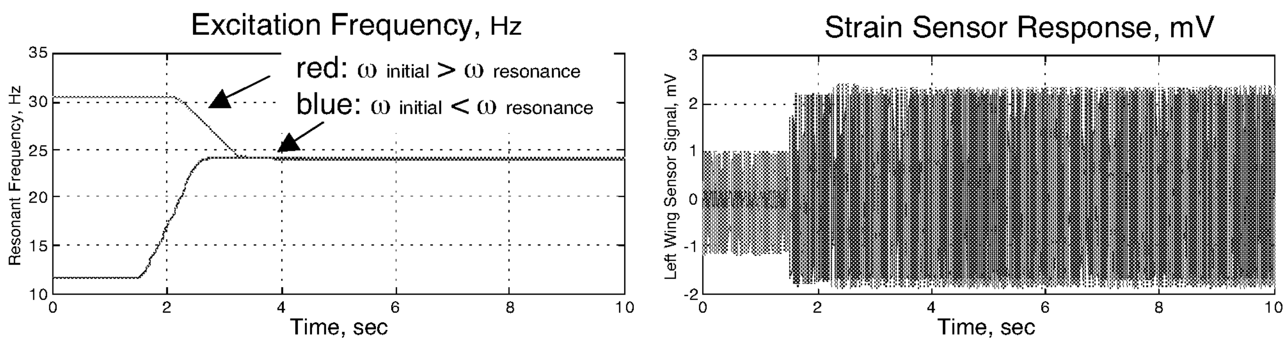


Figure 2. Closed-loop resonant capture time histories showing excitation frequency and strain-rate sensor response.

Future Work:
Future research will extend the pvdf feedback concept to drive resonant excitation inputs from multiple actuators for feedback control of flapping kinematics. Another topic that will be investigated is the incorporation of Langley-developed electrostrictive polymer actuation materials into the resonant flapping system.[4] Continued use of reduced pressure testing will provide data for estimation of aerodynamic damping influence on the resonant frequencies.

External Partners:
Under a cooperative agreement with Vanderbilt University, NASA is leveraging off previous DARPA-funded flapping flight research to provide a testbed for dynamic modeling, testing and control design.[5] Consultation with researchers at the University of Texas in Austin is providing mechanization and actuation insights from insect and avian morphological perspectives.

Documentation/References:

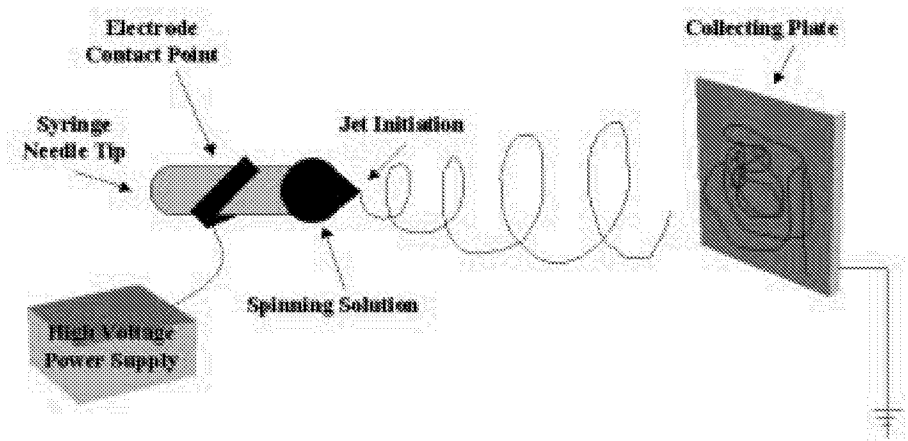
1. Frampton, K. D. *An Elastodynamic Ornithoptic Flying Robotic Insect*. Informal Presentation at LaRC Bioflight Workshop, August 10, 2000.
2. Raney, David L. *Dynamic Modeling and Control of Resonant Micro-Aerial Vehicles*. Informal Presentation at LaRC Bioflight Workshop, August 10, 2000.
3. Dickinson, M. H.; Lehmann, F.; Sane, S. P. *Wing Rotation and the Aerodynamic Basis of Insect Flight*. Science, Vol. 284, June 1999, pp.1954-1960.
4. Frampton, K.D.; Goldfarb, M. *Passive Aeroelastic Tailoring for Optimal Flapping Wings*. Proceeding of Conference on Fixed, Flapping and Rotary Winged Vehicles for Very Low Reynolds Numbers, Notre Dame, Indiana, June 2000.
5. Pawlowski, Kristin; Su, Ji; Raney, David L.; Siochi, Emilie J. *Electroactive Polymers for Development of a Micro-Air Vehicle Wing*. SPIE Symposium on Smart Structures and Materials, March 17-21, 2002, San Diego, California (pending).

BIOSANT FY 2001 Research Summary

Biologically Inspired Fabrication of Electroactive MAV Wings

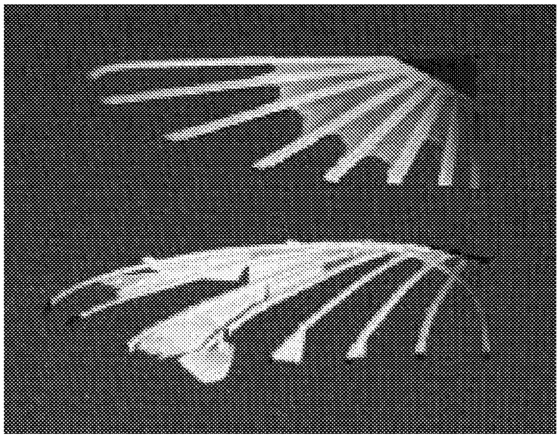
Emilie J. Siochi, 757-864-4279, e.j.siochi@larc.nasa.gov
Advanced Materials & Processing Branch, Structures and Materials Competency

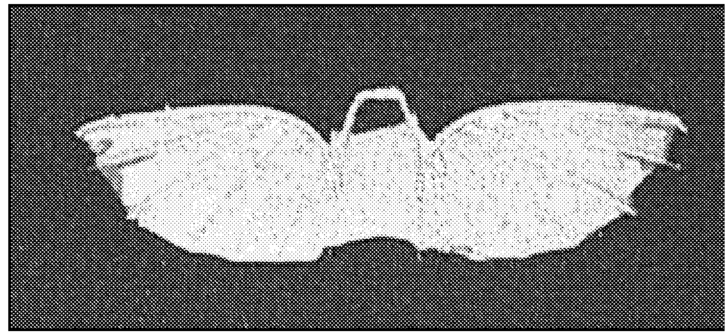
Background Information:
Electrospinning is a processing method that yields very fine polymer fibers. The basic experimental set-up shown below consists of a charged polymer solution that is fed through a small opening (usually a needle or pipette tip). The charged solution is drawn toward a grounded collecting plate as a jet. During jet travel, the solvent gradually evaporates, and a charged polymer fiber builds up on the collecting plate. The charges on the fibers eventually dissipate, as they are neutralized by the surrounding environment. The final product of the process is a nonwoven fiber mat composed of tiny fibers with diameters on the order of nanometers to microns.



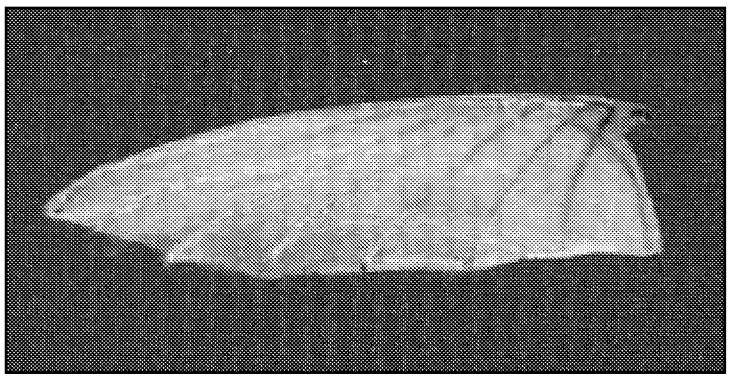
Objective of Current Work:
The objective of this project is to explore electrospinning as a new processing method of electroactive polymers. The goal is to be able to control the deposition and orientation of the fibers being collected on the target to allow fabrication of a material that can be used as an electrically responsive wing skin.

Accomplishments/Data Obtained:
Over the past year, parameters for the proper spinning of an electroactive polymer mat onto an open target (airframe) were determined. The progress of that task can be seen in the improvement of the spun wings shown in figures 1a-1c below. Figure 1C was the result of having the best combination of polymer solution characteristics and spinning parameters such as applied voltage and collecting plate distance, so far. The incorrect combination of any of the above parameters can result in failure to create a mat between the airframe spars as shown in figure 1a, to a less fibrous material as shown in figure 1b.





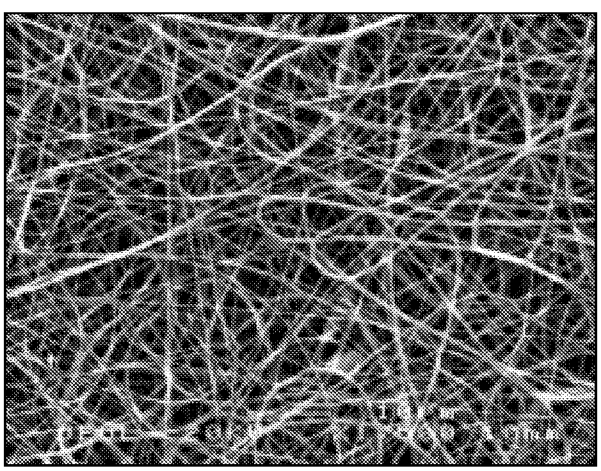
(A) (B)

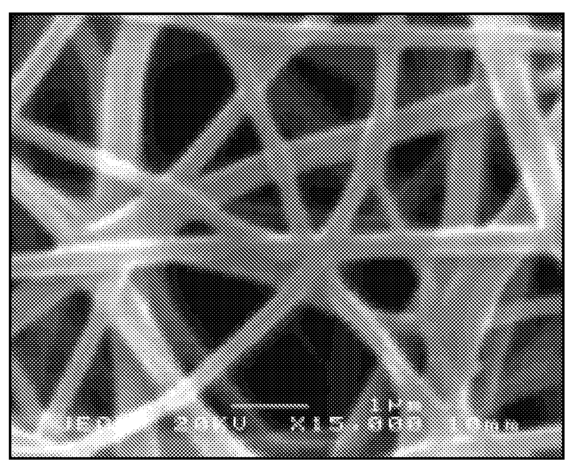


(C)

Figure 1. Effect of electrospinning parameters on quality of spun wings.

Characterization of the spun mat includes microscopy to investigate the uniformity of fiber diameters spun. Some examples of the data obtained are shown below:





(A) (B)

Figure 2. Scanning electron micrographs of electrospun fibers.

Figure 2a shows good uniformity of fiber diameter, with the enlarged photo in figure 2b revealing that fiber diameters are 200 – 400 nm across.

Some of the spun fibers were twisted to form ‘tendons’. These ‘tendons’ were tested for electroactivity. The best response appeared to be produced by a 3KV sine wave (peak-to-peak) at about 2.8Hz. There was no real force behind this motion, because as soon as a tiny load was applied, the motion stopped altogether (the tendon seemed barely able to move under its own weight.) The largest and thickest tendon appeared to produce no response at all. Surprisingly, the best response was produced by the thinner samples.

For the graphite-epoxy wing with the polymer fiber membrane, the best response appeared to be produced by a 3KV sine wave at about 6.7Hz. This input produced a barely perceptible vibration of the wing structure. The motion was very slight and it went away altogether as the input frequency was shifted from about 1Hz above or below the (apparently resonant) frequency of 6.7Hz.

Lessons Learned:
An extensive literature search on electrospinning revealed that it’s a method discovered by Lord Rayleigh in the late 19^{th} century. However, absence of practical use resulted in its abandonment so that there was about a 30-year gap where there was no published literature. Interest in this process was rekindled in the ‘70s because of potential biomedical applications. Since then, much of the literature is results of trial and error experiments to spin fibers from various polymers. There is little research towards a fundamental understanding of how the process can be controlled to yield fibers of uniform characteristics.

Future Work:
Results clearly show that deposition of fibers on the collecting plate is not well controlled yielding randomly oriented mats. Work is underway to modify the experimental set-up to correct this problem. It is anticipated that increased orientation will yield greater response to applied voltage. In addition, suitable fiber and mat analysis methods are being developed in order to obtain mechanical property information on the spun materials.

Team
This project is a collaborative effort between researchers in the Advanced Materials and Processing Branch and the Dynamics and Controls Branch. Members of the AMPB team are Kristin Pawlowski, Harry Belvin, Ji Su, Joycelyn Harrison and Mia Siochi. Researchers from DCB are Dave Raney and Marty Waszak. This research also represents a portion of a larger effort that is funded in the SLMFST project in AVST of NASA Langley.

Appendix

Morphing Project Team FY 2001

Robert G. Bryant r.g.bryant@larc.nasa.gov	Manager, Smart Technologies area 757-864-4262
David E. Cox d.e.cox@larc.nasa.gov	Manager, Biologically Inspired Flight Systems area 757-864-6658
Nancy M. Holloway n.m.holloway@larc.nasa.gov	Systems Engineering Competency Representative 757-864-7849
Lucas G. Horta l.g.horta@larc.nasa.gov	Manager, Adaptive Structures Morphing area 757-864-4352
Anna-Maria R. McGowan a.r.mcgowan@larc.nasa.gov	Manager, Morphing Project 757-864-1700
Sharon L. Padula s.l.padula@larc.nasa.gov	Aerospace Systems, Concepts & Analysis Competency Representative 757-864-2807
Emilie J. Siochi e.j.siochi@larc.nasa.gov	Manager, BIOSANT area 757-864-4279
Anthony E. Washburn a.e.washburn@larc.nasa.gov	Manager, Micro Aero Adaptive Control area 757-864-1290

Formal Publications

1. Allan, Brian G.; Juang, Jer-Nan; Raney, David L.; Seifert, A.; Pack, Latunia G.; Brown, Donald E. *Closed-Loop Separation Control using Oscillatory Flow Excitation*. ICASE Report 2000-32.

2. Anders, John B. Anders. *Biomimetic Flow Control*. AIAA Paper 2000-2543. Presented at the AIAA Fluids 2000 Conference, Denver, Colorado, June 19-22, 2000.

3. Antcliff, Richard R., McGowan, Anna-Maria R. *Active Control Technology at NASA Langley Research Center*. North Atlantic Treaty Organization, Research & Technology Organization Symposium on Active Control Technology For Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles And Sea Vehicles, Braunschweig, Germany, May 8-11, 2000.

4. Cabell, R. H., and Gibbs, G. P. *Hybrid active/passive control of sound radiation from panels with constrained layer damping and model predictive feedback control*. Proceedings of Noise-Con 2000, December 3-5, 2000, Newport Beach, California.

5. Chen, F. J. *Development of Synthetic Jet Actuators for Active Flow Control at NASA Langley*. Presented at the AIAA Fluid 2000 Conference, AIAA Paper 2000-2405, June 19-22, 2000, Denver, Colorado.

6. Chen, F. J. *Virtual Shaping of a Two-dimensional NACA 0015 Airfoil Using Synthetic Jet Actuator*. Submitted to the 1st AIAA Flow Control Conference, June 24-27, 2002,

7. Choi, Sang H., Golembiewski. Walter T., Song, Kyo D. Song. *Networked Rectenna Array for Smart Material Actuators*. Proceedings of 35th IECEC, AIAA 2000-3066, Las Vegas, Nevada, July 31-August 3, 2000.

8. Choi, Sang, Golembiewski. Walter T., Song, Kyo D., and Bryant, Robert G. *Networked Rectenna Array with Power Allocation and Distribution Circuit for Smart Material Actuators*. SPIE's 8th International Symposium on Smart Structures and Materials, Newport Beach, California, Vol. 4334, pp. 372-381, March 4-8, 2001.

9. Contract report for ATI demonstrator, model # RBL-01-0183.

10. Contract report for DEI demonstrator, model # RBL-01-0184.

11. Cook, Andrea M. *Genetic Algorithm Approaches to Optimizing the Location and Number of Smart Actuators on an Aircraft Wing*. Master's Thesis, Purdue University, December 2000.

12. Cook, Andrea M. and Crossley, William A. *Investigation of GA Approaches for Smart Actuator Placement for Aircraft Maneuvering*. 39th AIAA Aerospace Sciences Meeting, January 2001, Reno, Nevada.

Formal Publications (Cont'd)

13. Dunne, J. P., Pitt, D. M., White E. V. and Garcia, E.: *Ground Demonstration of the Smart Inlet*. AIAA Paper 2000-1630. Presented at the 41st Structures, Structural Dynamics, and Materials Conference, April 3-6, 2000, Atlanta, Georgia.

14. Ettinger, S. M.; Nechyba, M. C.; Ifju, P. G.; and Waszak, M. R. *Towards Flight Autonomy: Vision-Based Horizon Detection for Micro Air Vehicles*. To appear in proceedings of AIAA Aerospace Sciences Meeting, Reno, Nevada, January 2002.

15. Ettinger, S. M.; Nechyba, M. C.; Ifju, P. G.; and Waszak, M. R. *Vision-Guided Flight Stability and Autonomy for Micro Air Vehicles*. To appear in proceedings of AIAA Aerospace Sciences Meeting, Reno, Nevada, January 2002.

16. Fleming, G. A.; Bartram, S. M.; Waszak, M. R.; and Jenkins, L. N. *Projection Moiré Interferometry Measurements of Micro Air Vehicle Wings*. SPIE Paper No. 4448-16. Presented at the SPIE conference on Optical Diagnostics for Fluids, Solids, and Combustion, part of the SPIE International Symposium on Optical Science and Technology, San Diego, California, July 29-August 3, 2001.

17. Frampton, K. D. *An Elastodynamic Ornithoptic Flying Robotic Insect*. Informal Presentation at LaRC Bioflight Workshop, August 10, 2000.

18. Frampton, K.D.; Goldfarb, M. *Passive Aeroelastic Tailoring for Optimal Flapping Wings*. Proceeding of Conference on Fixed, Flapping and Rotary Winged Vehicles for Very Low Reynolds Numbers, Notre Dame, Indiana, June 2000.

19. Fraunhofer USA – Delaware. *Fabrication of Gamma Titanium Aluminide Closed-Cell Foams*. Final Report, September 2001.

20. Harrison, J. S. and Ounaies, Z.: *Piezoelectric Polymers*. Encyclopedia of Smart Materials, Ed. A. Biderman, John Wiley and Sons, submitted for publication.

21. Horta, L. G., Reaves, M. C., and Voracek, D. F. *A Probabilistic Approach to Model Update*. Proceedings of the First Annual Probabilistic Methods Conference, June 18-19, 2001, Newport Beach, California. Also NASA TM-2001-18097.

22. Ifju, P. G.; Jenkins, D. A.; Ettinger, S. J.; Lian, Y.; Shyy, W.; and Waszak, M. R.: *Flexible-Wing-Based Micro Air Vehicles*. AIAA Paper No. 2002-0705. To appear in proceedings of AIAA Aerospace Sciences Meeting, Reno, Nevada, January 2002.

23. Kudva, J. N.; Sanders, B.; Garcia, E.: *Overview of the DARPA/AFRL/NASA Smart Wing Phase 2 Program*. Presented at the SPIE's 9th Annual Symposium on Smart Structures and Materials, Vol. 4698, Paper No. 4698-04, 2002. Expected publication date, fall 2002.

Formal Publications (Cont'd)

24. Kudva, J. N.; Sanders, B.; Pinkerton-Florance, J.; Garcia, E.: *Overview of the DARPA/AFRL/NASA Smart Wing Phase 2 Program.* Presented at the SPIE Conference on Smart Structures and Materials, Industrial and Commercial Applications of Smart Structures Technologies, Vol. 4332, Paper No. 4332-48, 2001.

25. Lin, C. and Juang, J. *Self-tuning of Design Variables for Generalized Predictive Control.* NASA TM-2000-210619.

26. Martin, C. A.; et al: *Design, Fabrication and Testing of the Scaled Wind Tunnel Model for the Smart Wing Phase 2 Program.* SPIE's 9th Annual Symposium on Smart Structures and Materials, Vol. 4698, Paper No. 4698-05, 2002. Expected publication date, fall 2002.

27. McGowan, A. R. *Research on Adaptive Aerospace Vehicle Technologies at NASA Langley Research Center.* Adaptronic Congress, Paper 1, Berlin, Germany, April 2001.

28. McGowan, A-M. R., Horta, L. G., Harrison, J. S., and Raney, D. L. *Research Activities within NASA's Morphing Program.* RTO AVT Specialist Meeting on "Structural Aspects of Flexible Aircraft Control," RTO MP-36, Paper 13, Ottawa, Canada, October 1999.

29. McGowan, A-M., R.: *Research and Future Directions on Smart Structures and Materials in Aerospace Vehicles.* Presented at the 39th Annual Aircraft Symposium, October 29-31, 2001, Gifu, Japan.

30. Pack, L.G., Schaeffler, N.W., Yao, C.S., and Seifert, A. *Active Control of Flow Separation from the Slat Shoulder of a Supercritical Airfoil.* Extended Abstract Submitted to the 1st AIAA Flow Control Meeting, June 24-27, 2002, St. Louis, Missouri.

31. Padula, Sharon L., Rogers, James L., and Raney, David L. *MDO Techniques and Novel Aircraft Control Systems.* AIAA Paper No. 2000-4848.

32. Padula, Sharon L.; Rogers, James L.; Raney, David L. *Multidisciplinary Techniques and Novel Aircraft Control Systems.* AIAA Paper No. 2000-4848.

33. Pawlowski, Kristin; Su, Ji; Raney, David L.; Siochi, Emilie J. *Electroactive Polymers for Development of a Micro-Air Vehicle Wing.* SPIE Symposium on Smart Structures and Materials, March 17-21, 2002, San Diego, California (pending).

34. Pitt, D. M., Dunne, J. P., White, E. V., Garcia, E.: *SAMPSON Smart Inlet SMA Powered Adaptive Lip Design and Static Test.* AIAA-01-1359. Presented at the 42nd Structures, Structural Dynamics, and Materials Conference, April 16-20, 2001, Seattle Washington.

35. Pitt, D. M., Dunne, J. P., White, E. V., Garcia, E.: *Wind Tunnel Demonstration of the SAMPSON Smart Inlet.* Presented at the 8th Annual International Symposium on Smart Structures and Materials Conference, March 4-8, 2001, Newport Beach, California.

Formal Publications (Cont'd)

36. Pitt, D. M.: *SAMPSON Smart Inlet First Entry – Test Report*. Boeing report, July 24, 2000.

37. Raney, D. L., Montgomery, R. C., Green, L. L. and Park, M. A. *Flight Control using Distributed Shape-Change Effector Arrays*. AIAA Paper 2000-1560, April 2000.

38. Raney, David L. *Dynamic Modeling and Control of Resonant Micro-Aerial Vehicles*. Informal Presentation at LaRC Bioflight Workshop, August 10, 2000.

39. Reaves, M. C., and Horta, L. G.: *Test Cases for Modeling and Validation of Structures with Piezoelectric Actuators*. AIAA 2001-1466. Proceedings of the AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, Seattle, Washington, April 16-19, 2001.

40. Scherer, L. B.; et al: *DARPA / AFRL Smart Wing Phase 2 Wind Tunnel Test Results*. Presented at the SPIE's 9th Annual Symposium on Smart Structures and Materials, Vol. 4698, Paper No. 4698-07, 2002. Expected publication date, fall 2002.

41. Seifert, A. and Pack, L.G. *Active Control of Separated Flows on Generic Configurations at High Reynolds Numbers*. Submitted to AIAA Journal 2001.

42. *Smart Materials and Structures – Smart Wing Phase 2*. Contract Final Report, Contract Number F33615-97-C-3213. Expected Publication, Fall 2002.

43. Song, Kyo D., Golembiewski. Walter T., and Choi, Sang H. *Design of Power Allocation and Distribution Circuit with Rectenna Array for Smart Material Actuators*. Proceedings of International Symposium on Smart Structures and Microsystems 2000, Hong Kong, October 19-21, 2000.

44. Su, J., Costen, R., and Harrison, J. S.: *Design and Fabrication of Bending Actuators Using Electrostrictive Graft Elastomers*. Proceedings of SPIE Smart Structures and Materials, 2001.

45. Su, J., Harrison, J. S., and St. Clair, T.: *Novel Polymeric Elastomers for Actuation*. Proceedings of IEEE International Symposium on Application of Ferroelectrics, 2001.

46. Su, J., Harrison, J. S., St. Clair, T., Bar-Cohen, Y., and Leary, S.: *Electrostrictive Graft Elastomers and Applications*. Proceedings of MRS Fall Meeting, Vol. 600, 2000.

47. Su, J., Ounaies, Z., and Harrison, J. S.: *Ferroelectric and Piezoelectric Properties of Blends of Polyvinylidene-trifluoroethylene and Graft Elastomer*. Proceedings of MRS Fall Meeting, Vol. 600, 2000.

Formal Publications (Cont'd)

48. Su, J., Ounaies, Z., Harrison, J. S., Bar-Cohen, Y., and Leary, S.: *Electromechanically Active Polymer Blends for Actuation*. Proceedings of SPIE-Smart Structures and Materials, Vol. 3987, pp. 65-72, 2000.

49. Turner*, Travis L.; Lach, Cynthia L.; Cano, Roberto J. *Fabrication and Characterization of SMA Hybrid Composites*. SPIE's 8th Annual Internat'l Symposium on Smart Structures and Materials, March 4-8, 2001, Newport Beach, California, SPIE 4333-60.

50. Turner, Travis L. *A New Thermoelastic Model for Analysis of Shape Memory Alloy Hybrid Composites*. Journal Intell. Mat.. Sys. & Struct. 11(5) 382-394, May 2000.

51. Turner, Travis L. *Experimental Validation of a Thermoelastic Model for SMA Hybrid Composites. SPIE's 8th Annual Internat'l Symposium on Smart Structures and Materials*, March 4-8, 2001, Newport Beach, California, SPIE 4326-24.

52. Turner, Travis L. *Thermomechanical Response of Shape Memory Alloy Hybrid Composites*. NASA TM-2001-210656, January 2001.

53. Venkataraman, S., Zhu, H., Sankar, B.V., and Haftka, R. T. *Optimum Design of a Functionally Graded Metallic Foam Thermal Insulation*. Proceedings of the American Society for Composites-16th Technical Conference, Blacksburg, Virginia, September 9-12, 2001.

54. Voracek, D., Reaves, M. C., Horta, L. G., Potter, S. *Ground and Flight Test Structural Excitation using Piezoelectric Actuators*. Submitted to AIAA 2002, AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Denver, Colorado, April 22-25, 2002

55. Wang, D. P.; et al: *Development, Control, and Test Results of High Rate, Hingeless Trailing Edge Control Surface for the Smart Wing Phase 2 Wind Tunnel Model*. Presented at the SPIE's 9th Annual Symposium on Smart Structures and Materials, Vol. 4698, Paper No. 4698-06, 2002. Expected publication date, fall 2002.

56. Washburn, A. E. *NASA Micro-Aero-Adaptive Control*. SPIE's 8th Annual International Symposium on Smart Structures and Materials, SPIE paper 4332-39, March 2001.

57. Waszak, M. R.; Jenkins, L. N.; and Ifju, P. *Stability and Control Properties of an Aeroelastic Fixed Wing Micro Aerial Vehicle*. AIAA Paper No. 2001-4005. Presented at the AIAA Atmospheric Flight Mechanics Conference, Montreal, Quebec, Canada, August 6–9, 2001.

Formal Publications (Cont'd)

58. Wilkie, W. K., R. G. Bryant, J. W. High, R. L. Fox, R. F. Hellbaum, A. Jalink, Jr., B. D. Little and P. H. Mirick. *Low-Cost Piezoelectric Actuator for Structural Control Applications*. Proceedings of the SPIE, Smart Structures and Materials 2000 - Industrial and Commercial Applications of Smart Structures Technologies, (3991), 323, 2000.

59. Wilkie, W. Keats, High, James W. *Design, Fabrication and Characterization of a Conformable, High-Performance Anisotropic Piezoelectric Composite Device for Structural Control Applications*. NASA TM, draft in progress, December 2001.

60. Wlezien, R. W., Horner, G., McGowan, A. R., Padula, S., Scott, M. A., Silcox R., and Simpson, J. O. *The Aircraft Morphing Program*. Proceedings of the 37th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Long Beach, California, April 1998.

61. Zhu, H., Sankar, B.V., Haftka, R. T., and Venkataraman, S. *Minimum Mass Design of Insulation Made of Functionally Graded Material*. Accepted for presentation at the 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Denver, Colorado, April 22-25, 2002.

2001 Institute for Computer Applications in Science and Engineering (ICASE) Lecture Series on Morphing

http://www.icase.edu/series/Morphing/

In fiscal year 2001, a lecture series was initiated to broaden our awareness of innovative technologies and approaches. The lectures were conducted through the ICASE group at Langley Research Center.

1. Dudley, Robert: *Mechanisms of Animal Flight Maneuverability: Hummingbirds as Case Example*. University of Texas at Austin, May 7, 2001.

2. Morris, Stephen: *Micro Air Vehicle Design Optimization and Flight Test Results*. MLB Company, Palo Alto, California, May 23, 2001.

3. Dial, Kenneth: *Birds Morphing: Escaping the U-shaped Power Curve and Performing Extraordinary Maneuverability*. The University of Montana, June 29, 2001.

4. Kornbluh, Roy*: Dielectric Elastomer Actuators: Muscles that Morph*. SRI International, August 7, 2001.

5. Brei, Diann: *Smart Material Actuation Systems*. University of Michigan, Ann Arbor, August 27, 2001.

6. Carman, Gregory*: Investigating the Passive Damping Properties of Active Materials*. University of California, Los Angeles, October 3, 2001.

7. Bewley, Thomas: *Adjoint and Riccati: Essential Tools in the Analysis and Control of Transitional and Turbulent Flow System*. University of California, San Diego, October 23, 2001.

8. Weisshaar, Terrence: *Aeroelastic Tailoring for Energy Efficient Morphing Aircraft - Finding the Right Stuff*. Purdue University, October 25, 2001.

9. Chopra, Inderjit : *Review on the Status of Application of Smart Structures Technology to Rotorcraft Systems*. University of Maryland, College Park, October 31, 2001.

10. Grasmeyer, Joel: *Perspectives on Micro Air Vehicles and Electronic Packaging* AeroVironment, Inc., November 9, 2001.

Partnerships and Collaborations in the Morphing Project in Fiscal Year 2001

Adoptech Inc.
Advanced Technologies Inc.
Air Force Office Scientific Research
Air Force Research Laboratories
Applied Physics Labs
Arizona State University
Brown University
Cincinnati Machine
Composite Optics
Defense Advanced Research Projects Agency
Duke University
Dynamic Engineering Inc.
Electric Boat
Florida State University
Fraunhofer Inc
Georgia Tech Research Institute
Hampton University
Institute for Defense Analysis
Integral Wave Technologies
Johns Hopkins Applied Physics Lab
Jet Propulsion Laboratory
Lockheed Martin
Mississippi State University
Massachusetts Institute of Technology
MSC Software
NASA Dryden Flight Research Center
Norfolk State University
North Carolina State University
Northrop Grumman Corporation
Office of Naval Research
The Pennsylvania State University
Purdue University
Research Technology Institute
Tel Aviv University
Texas Agricultural & Mechanical University
The Boeing Company
U. S. Army
University of Arkansas
University of Florida
University of Michigan
University of Notre Dame
University of Tennessee
University of Texas at Austin
University of Washington
University of Wyoming
Vanderbilt University
Virginia Institute of Marine Sciences
Virginia Polytechnic Institute and State University

Partnerships and collaborations with external organizations are a vital part of the research in the Morphing Project.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
08-2002	Technical Memorandum	

4. TITLE AND SUBTITLE
AVST Morphing Project Research Summaries in Fiscal Year 2001

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Anna-Maria R. McGowan

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
706-32-41-20

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-18204

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM-2002-211769

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited Distribution: Standard
Subject Category 08
Availability: NASA CASI 301-621-0390

13. SUPPLEMENTARY NOTES
An electronic version can be found at http://techreports.larc.nasa.gov/ltrs/ or http://techreports.larc.nasa.gov/cgi-bin/NTRS

14. ABSTRACT
The Morphing project at the National Aeronautics and Space Agency's Langley Research Center is part of the Aerospace Vehicle Systems Program Office that conducts fundamental research on advanced technologies for future flight vehicles. The objectives of the Morphing project are to develop and assess advanced technologies and integrated component concepts to enable efficient, multi-point adaptability in air and space vehicles. In the context of the project, the word "morphing" is defined as "efficient, multi-point adaptability" and may include micro or macro, structural or fluidic approaches. The current document on the Morphing project is a compilation of research summaries and other information on the project from fiscal year 2001. The focus of this document is to provide a brief overview of the project content, technical results and lessons learned from fiscal year 2001.

15. SUBJECT TERMS
Morphing, Micro-Aero-Adaptive Control, Smart Technologies, Adaptive Structural Morphing, Biologically Inspired Flight Systems, BIOSANT

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	108	(301) 621-0390